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CHARACTERIZATION OF LASER-TEXTURED SURFACES – A REVIEW

BY

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Abstract. Laser surface texturing (LST) is an advanced and highly versatile technique for tailoring the surface properties of biopolymeric materials, with broad applications in biomedical, automotive, and industrial domains. This review investigates the influence of LST on the mechanical, tribological, thermal, and wettability characteristics of both polymeric and biopolymeric surfaces, with the overarching goal of enhancing their performance and durability. The methodology centers on laser ablation, employed to generate microstructures with various geometries, while optimizing critical processing parameters such as laser fluence, scanning speed, and pulse duration. The review encompasses a wide range of materials, including PLA, PHA, PEEK, HDPE, and PET, examining their responses to laser-induced surface modifications. Experimental investigations include mechanical tests (microhardness, tensile strength), tribological assessments (coefficient of friction, wear resistance), thermal analyses (DSC, TGA), and wettability measurements (contact angle). In addition, the impact of different texturing patterns–such as linear, hexagonal, and circular–is evaluated to determine their specific effects on material behavior.

Keywords: biodegradable polymer; surface texturing, wettability, degradation, friction coefficient, wear resistance.

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1. Introduction

In recent decades, the rapid advancement of material processing technologies has opened new horizons for optimizing the functional performance of surfaces. In this context, surface texturing has emerged as a promising and versatile technique, playing a crucial role in enhancing the physical, mechanical, chemical, and technological properties of materials. Among the many available methods, laser surface texturing (LST) stands out as a cutting-edge solution due to its high precision, energy efficiency, and minimal environmental impact.

Texturing involves modifying the micro- and nano-topography of a surface to achieve specific functionality. It can take various geometric forms–from hemispheres and elliptical cavities to honeycomb patterns and grooves–each tailored to serve distinct purposes such as reducing the coefficient of friction, increasing durability, or improving light absorption. Due to these characteristics, LST is employed in a wide range of industrial and biomedical applications: from automotive components and solar panels to medical implants and microelectronic circuits.

The fundamental principle of laser texturing is based on ablation, a process in which the surface material is melted and evaporated by a focused, high-intensity laser beam. Unlike other methods such as chemical etching or abrasive blasting, laser texturing stands out for its lack of consumables, which leads to reduced operational costs, minimal maintenance, and a safer working environment for operators. This technique allows for precise control over process parameters (such as energy density, depth, and geometry of the micro-cavities), enabling highly tailored surface functionalization for a wide variety of materials including metals, ceramics, and especially biopolymers.

In particular, for biopolymers–biodegradable and biocompatible materials derived from renewable sources–laser texturing holds strategic importance. Biopolymers such as PLA, PHA, and chitosan are widely used in fields such as regenerative medicine, the food and pharmaceutical industries, and eco-friendly applications. Texturing these materials enhances their tribological, mechanical, or wettability properties, which are crucial for integration into biological environments or demanding technical conditions. For instance, in medical implants, textured structures can increase biocompatibility and osteoconductivity, promoting better integration into biological tissues and reducing implant rejection rates.

The applications of LST are supported by extensive experimental research. Recent studies have shown that laser texturing has significantly improved the durability of automotive components, increased the efficiency of electronic devices, and enabled the development of advanced biomedical materials such as textured sutures and customized surgical meshes. In microelectronics, LST contributes to the creation of fine structures on conductive substrates, directly impacting the energy efficiency of devices.

Therefore, laser surface texturing of biopolymer-based materials represents a highly promising research direction, combining material sustainability with high-precision processing efficiency. This technology aligns with both industrial demands for performance and durability, and environmental requirements, opening new perspectives in the design of smart materials and high-tech applications.

2. The Influence of LST on the Properties of Polymers

2.1. The Influence of LST on Mechanical Properties

Laser Surface Texturing (LST) is an advanced method for modifying polymer surfaces, having a significant impact on their mechanical properties. The effect of LST depends on the type of polymer used and the parameters of the laser beam (Silberschmidt *et al.*, 2022).

When evaluating the influence of CO_2 laser irradiation on thin films of poly(L-lactic acid) (PLLA), an increase in microhardness (Table 1) and structural modifications adaptable to cellular requirements were observed. For HDPE and PET, tensile tests revealed a significant decrease in tensile strength: 27% for HDPE and 46% for PET (Fig. 1), (Di Siena *et al.*, 2023).

Table 1

Micromechanical properties presented as mean and standard deviation (X ± SD) determined by indentation testing for reference and irradiated samples (Tomanik et al., 2020)

Type of specimen	EIT (GPa)	HIT (MPa)	HV	hm (µm)	Noi (nJ)	Wp (nJ)
Ref	2.1 ± 0.9	200.5 ± 53.2	18.9 ± 5.0	6.1 ± 0.9	116.0 ± 46.7	145.7 ± 27.3
F1	3.4 ± 0.8	300.2 ± 54.9	28.3 ± 5.2	4.7 ± 0.5	80.6 ± 13.0	113.4 ± 5.6
F2	4.1 ± 1.0	429.6 ± 205.8	40.5 ± 19.4	4.3 ± 0.7	73.6 ± 7.3	117.3 ± 9.3
F3	0.4 ± 0.03	115.9 ± 17.7	10.9 ± 1.7	1.2 ± 0.4	376.6 ± 40.2	166.7 ± 25.0

Legend: E_{IT} - Young's modulus, H_{IT} - instrumented microhardness, HV -Vickers microhardness , hm - maximum indentation depth, We - elastic deformation energy, Wp - plastic deformation energy.

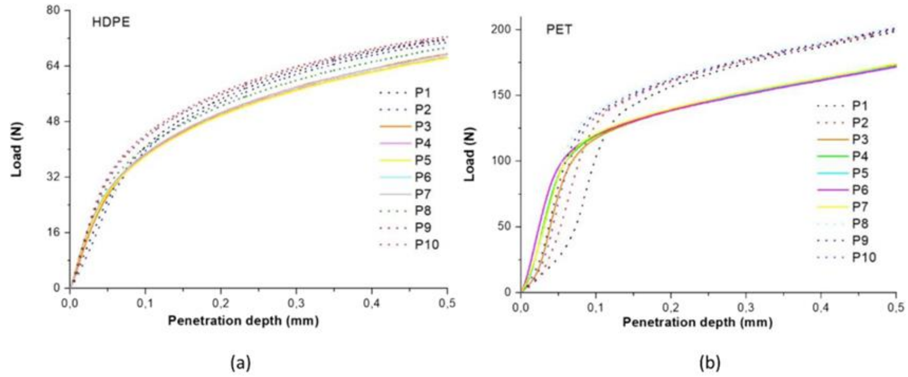


Fig. 1 – Results of FIMEC test on HDPE (a) and PET (b), (Di Siena *et al*., 2023).

The analysis of surface roughness modifications of PEEK and PEKK after laser treatments (Er:YAG, Nd:YAG, diode, femtosecond) was conducted using SEM imaging (Fig. 2), revealing distinct topographies for each type of treatment (Asik *et al*., 2023*)*. Laser texturing of polyethylene (PE) for adhesive bonding confirmed substantial increases in bond strength: 281% for circular textures and 491% for linear ones (Table 2), (Tofil *et al*., 2023).

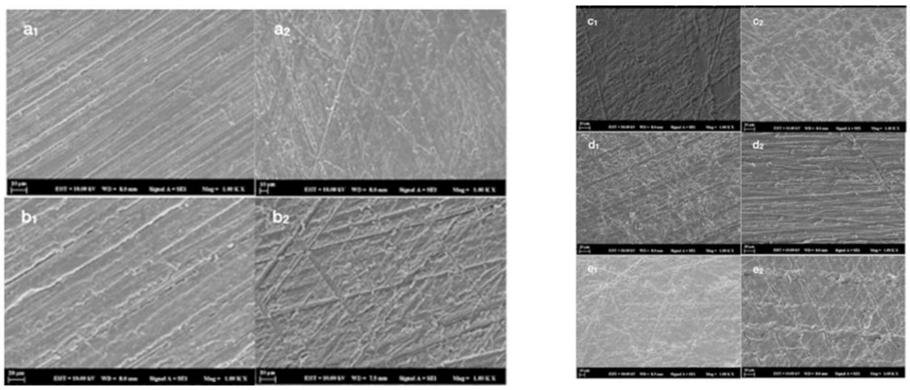


Fig. 2 – Scanning electron micro graphs (original magnification ×1000) of different surface treat ments. a1:PEEK Control, a2: PEKK Control, b1: PEEK Er: YAG Laser, b2: PEKK Er: YAG Laser, c1: PEEK Nd: YAG Laser, c2: PEKK Nd: YAG Laser, d1: PEEK Diode Laser, d2: PEKK Diode Laser, e1: PEEK Femtosecond Laser, e2: PEKK Femtosecond Laser (Asik *et al*., 2023).

Table 2
Average joint breaking strength results (Tofil et al., 2023)

	PE without Micropattern	PE with Circle Micropattern	PE with Perpendicular Lines Micropattern
Measurement 1, N	55	145	252
Measurement 2, N	42	134	235
Measurement 3, N	56	140	241
Measurement 4, N	48	138	249
Measurement 5, N	50	149	255
Average, N	50.2	141.2	246.4
Standard deviation, N	5.67	5.89	8.23
Min, N	42	134	235
Max, N	56	149	255
The average increase in strenght, %		281.27	490.84

For the biopolymer Arboblend V2 Nature, tests revealed variations in Young's modulus and microhardness depending on the applied texture and the number of passes (Figs. 4 and 5), (Mazurchevici *et al.*, 2023).

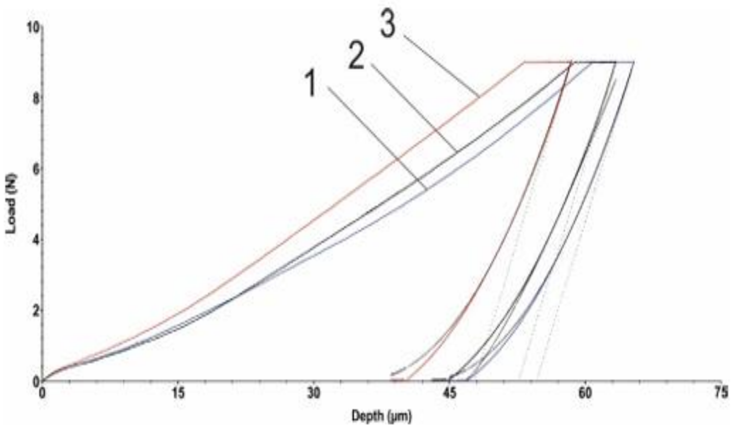


Fig. 3 – Hexagonal texture microindentation test (2 passes): 1, 2, 3–measurement (Mazurchevici *et al.*, 2023).

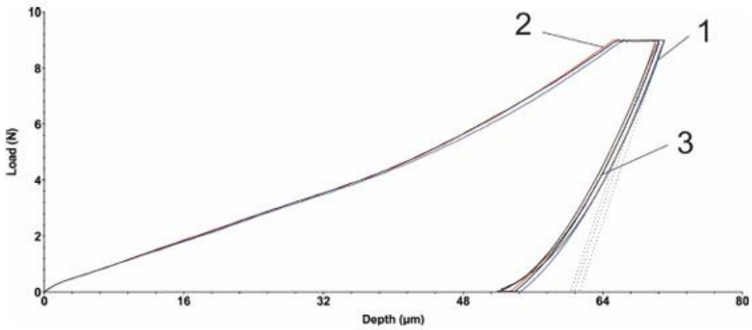


Fig. 4 – Square texture microindentation test (4 passes): 1, 2, 3–measurements (Mazurchevici *et al*., 2023).

The texturing of polyoxymethylene (POM) was optimized using the Grey-Taguchi method, showing that laser power influences texture depth, while scanning speed affects surface roughness. Predictive models exhibited low errors (Fig. 8), (Zhang *et al*., 2023*)*.

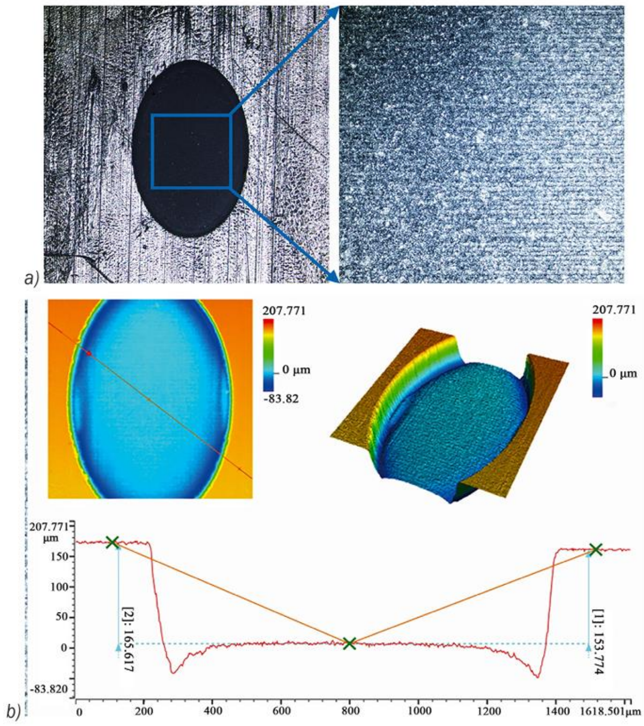


Fig. 5 – Measurement of a) surface roughness and b) depth (Zhang *et al*., 2023).

2.2. Improvement of Surface Tribological Behavior

Improving the tribological behavior of surfaces is a major objective in materials engineering, with implications in industries such as automotive, aerospace, and biomedical. Recent studies show that controlled textures can reduce the coefficient of friction by up to 80% (Table 3) and influence wear mechanisms including adhesion, abrasion, and fatigue (Fig. 6), (Han *et al.*, 2010).

The influence of texture geometry parameters on tribological performance is also analyzed, demonstrating that a higher aspect ratio can significantly reduce kinetic friction (Fig. 7), (Yasaka *et al.*, 2016). Laser treatment also increases surface microhardness, as shown in Fig. 8 (Sang *et al.*, 2023), and its effects are also observed for materials such as PEEK (Fig. 9), (Tomanik *et al.*, 2020).

Table 3
Stable values of friction coefficient for different types of PEEK materials(Sang et al., 2023)

Texture types	No texture	Linear texture	Mesh texture
Coefficient of friction	0.2147	0.1736	0.1428

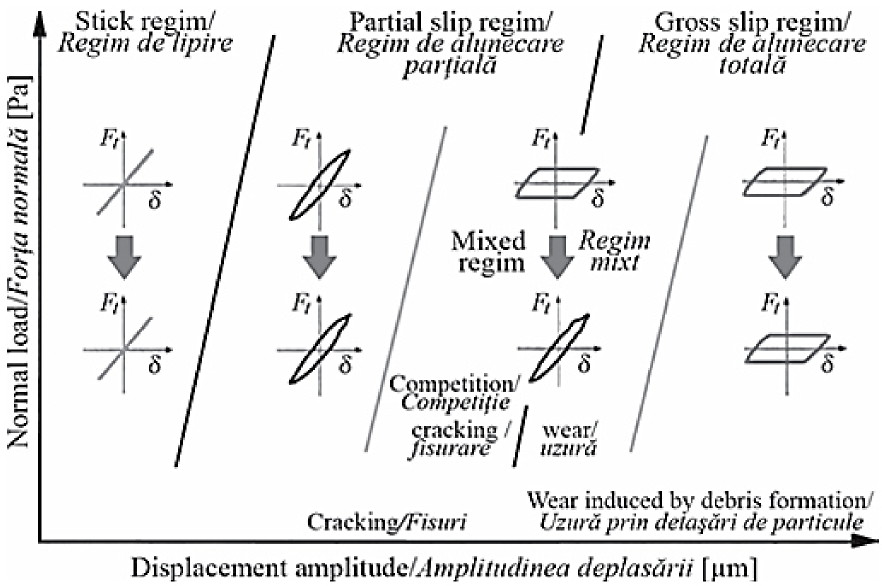


Fig. 6 – Fretting maps (Han *et al.*, 2010).

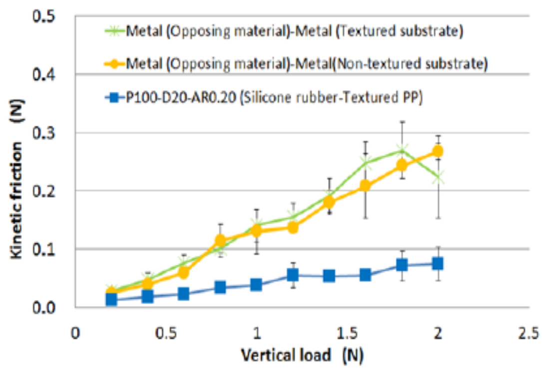


Fig. 7 – Kinetic friction (soft materials vs hard materials),
(Yasaka *et al.*, 2016).

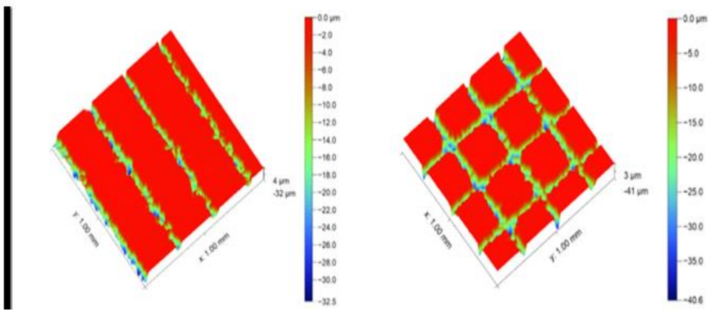


Fig. 8 – 3D morphology of PEEK materials surface with two texture types,
(Sang *et al.*, 2023).

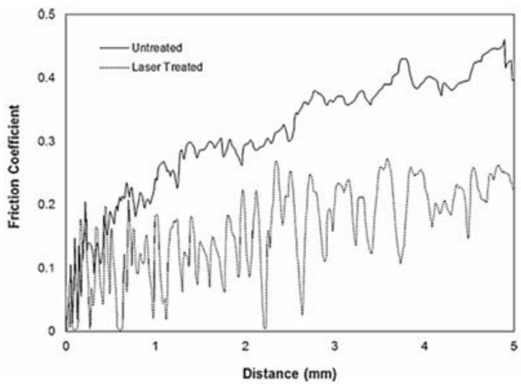


Fig. 9 – Friction coefficient along the laser treated and untreated surfaces,
(Tomanik *et al.*, 2020).

2.3. Analysis of the Thermal Properties of Polymers (DSC- Differential Scanning Calorimetry and TGA - Thermogravimetric Analysis

The knowledge of the thermal properties of polymers is essential for optimizing their processing and performance. Techniques such as DSC and TGA allow the evaluation of thermal stability, glass transition and melting temperatures, as well as behavior under degradation.

Polymers exhibit high thermal stability, with mass loss occurring at temperatures above 350°C. DSC highlights variations in glass transition temperatures depending on chemical composition (Fig. 10), (Yilbas *et al*., 2014). For HDPE and PET, it can be observed that laser irradiation influences crystallinity (Fig. 11), while TGA indicates significant degradation of HDPE at ~482°C, whereas PET shows superior stability (Fig. 12), (Di Siena *et al*., 2023).

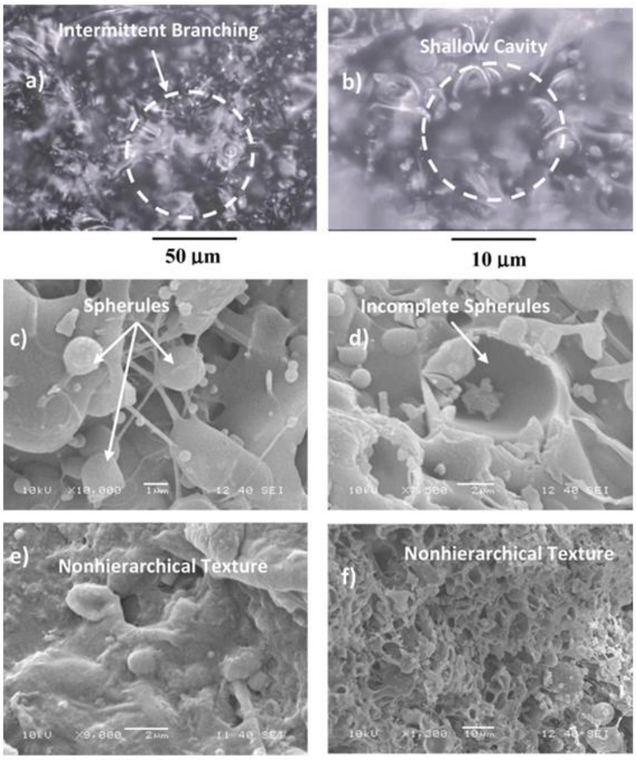


Fig. 10 – Optical images and SEM micrographs of laser treated surface: (a) optical image demonstrating the crystals formed at the surface and radial growth of crystals and intermittent branching, (b) laser produced fine size shallow cavity and spherules, (c) spherules formed at the surface, (d) incomplete spherules, and (e and f) nonhierarchical texture (Yilbas *et al.*, 2014).

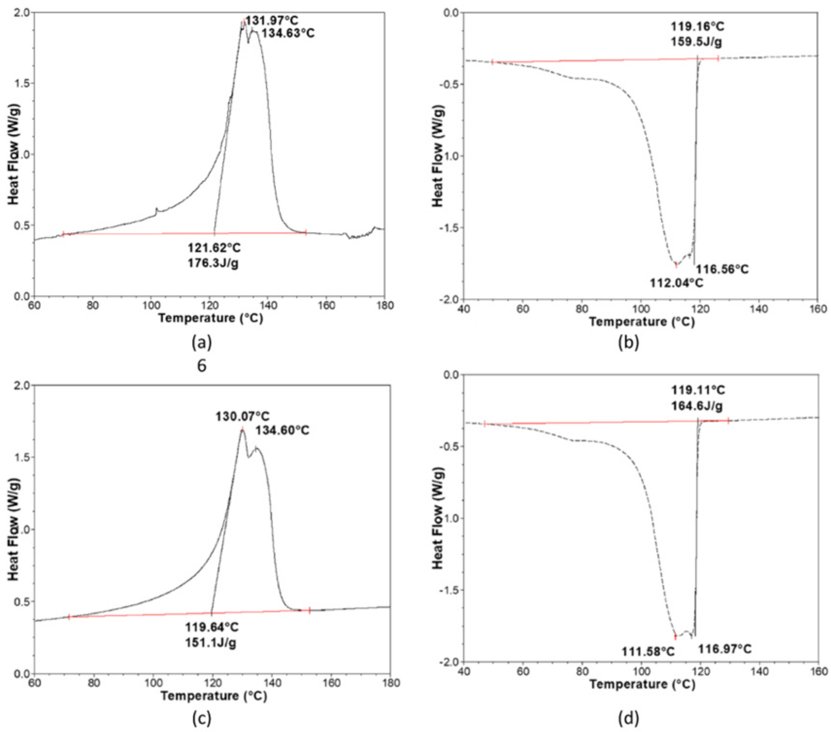


Fig. 11 – DSC curve of irradiated HDPE with both heating/cooling cycles: (a,c) evaluation of the melting temperature and enthalpy respectively during the first and second heating cycles; (b,d) evaluation of the crystallization temperature and enthalpy respectively during the first and second cooling cycles (Di Siena *et al*., 2023).

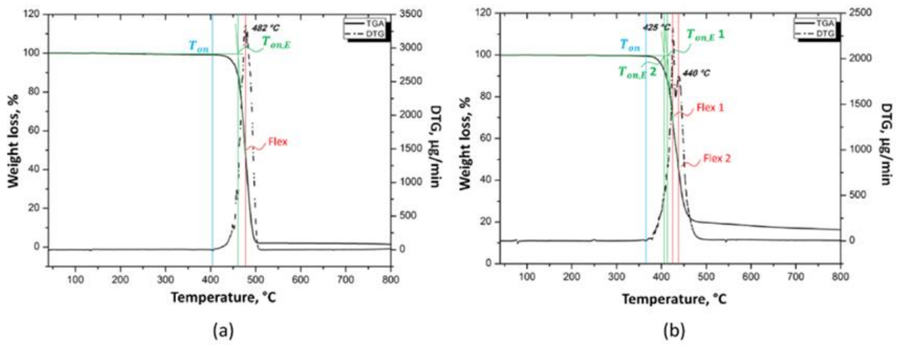


Fig. 12 – TGA curve (solid line) and DTG (dotted line) of HDPE (a) and PET (b), (Di Siena *et al*., 2023).

Laser experiments on PVC, PET, and PP have demonstrated three distinct ablation regimes: non-thermal, thermal, and saturation (Figs. 13 and 14). PVC and PET exhibit glassy-elastic transitions that amplify thermal effects, while PP, with a higher thermal capacity, limits ablation (Bernabeu *et al*., 2023). For PMMA processing with laser, studies on microchannels fabricated by CO_2 laser have shown that laser parameters influence the geometry of the resulting structures (Figs. 15 and 16). The incubation effect reduces the ablation threshold with multiple scans, optimizing processing precision (Li *et al*., 2024).

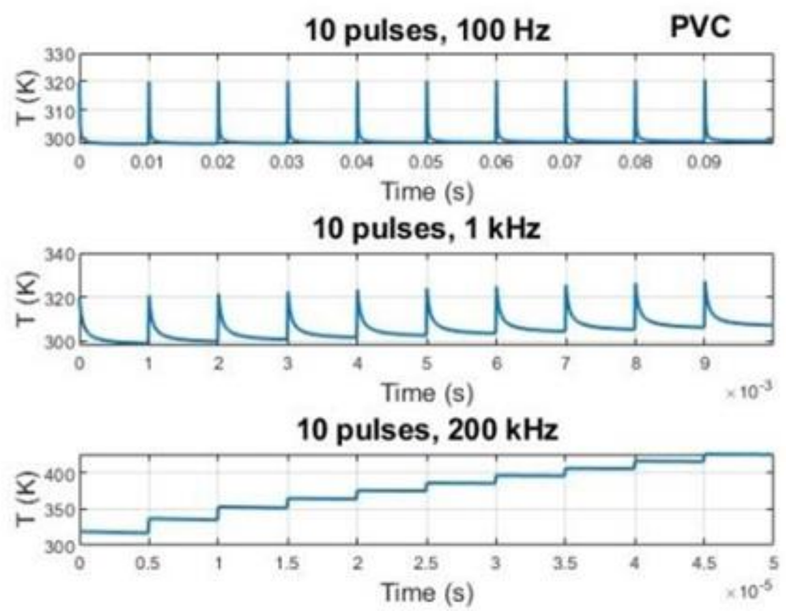
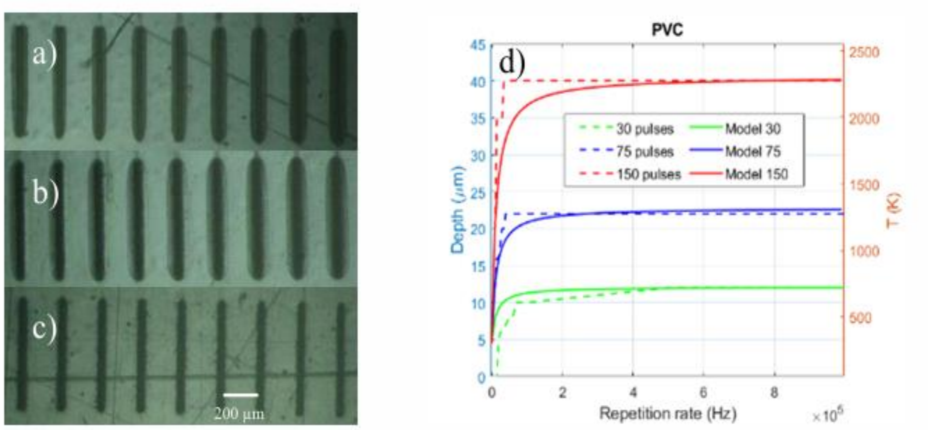


Fig. 13 – Simulations of PVC temperature profile for 10 pulses and 100 Hz, 1 kHz and 200 kHz for λ=515 nm conditions.



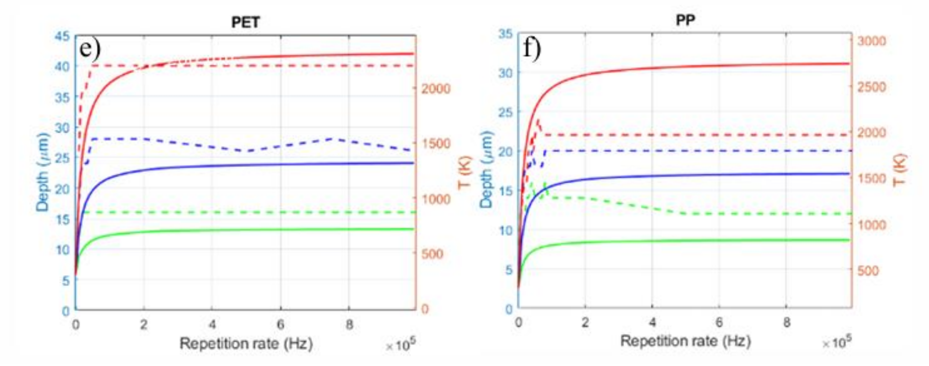


Fig. 14 – PVC (a), PET (b) and PP (c) irradiations at 515 nm with N=150 pulses and frequency increasing from right to left. (d-f) Measured irradiated lines depth (dashed lines, left axis) and temperature simulations at the centre of the spot (continuous lines, right axis) for 30 pulses (green), 75 pulses (blue) and 150 pulses (red)/spot area as functions of repetition rate for PVC (d), PET (e) and PP (f).

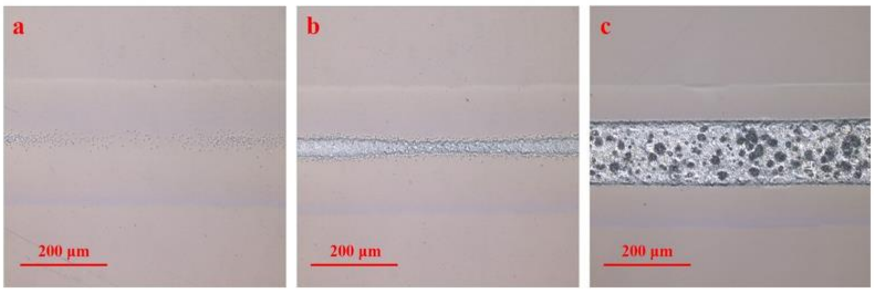
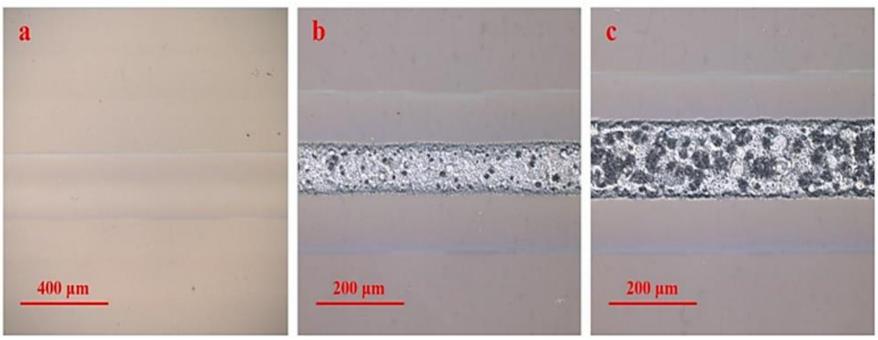


Fig. 15 – Ablation morphology on the surface of PMMA obtained with a single-pass laser scan with the following scanning speeds and laser energy densities: (a) 2700 mm/s, 2.06 J/cm^2; (b) 2600 mm/s, 2.14 J/cm^2; (c) 1800 mm/s, 3.10 J/cm^2.



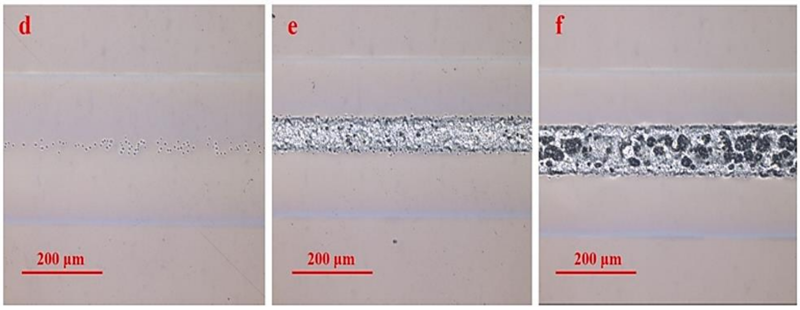
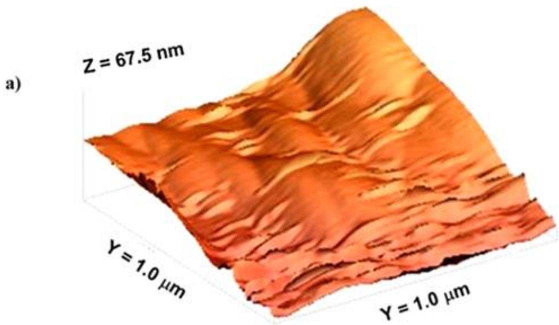


Fig. 16 – Ablation morphology on the surface of PMMA obtained with a multi-pass laser scanning system with the following scanning speeds, scanning numbers, and total laser energy density: (a) 3000 mm/s, 1 pass, 1.86 J/cm^2; (b) 3000 mm/s, 2 pass, 3.71 J/cm^2; (c) 3000 mm/s, 3 pass, 5.57 J/cm^2; (d) 6000 mm/s, 5 pass, 4.64 J/cm^2; (e) 6000 mm/s, 6 pass, 5.57 J/cm^2; (f) 6000 mm/s, 7 pass, 6.50 J/cm^2.

Thermal analysis of polymers is essential for understanding phase transitions, thermal stability, and the impact of laser irradiation. DSC and TGA allow for the optimization of material processing, and the use of CO_2 laser can be adjusted to achieve precise structures while minimizing undesirable thermal effects.

2.4. The Influence of LST on Surface Wettability

Laser Surface Texturing (LST) is a versatile technique used to modify the wettability of surfaces of various materials, influencing the contact angle (CA) between liquids and the surface. Studies have shown that, by optimizing laser parameters, surfaces can become superhydrophobic or superhydrophilic. When analyzing the hydrophobicity of polycarbonate glass treated with a CO_2 laser, the formation of micro/nanometric pores and an increase in roughness are observed (Fig. 17). Contact angle measurements on treated and untreated surfaces revealed significant differences (Fig. 18), (Yilbas *et al.*, 2014).



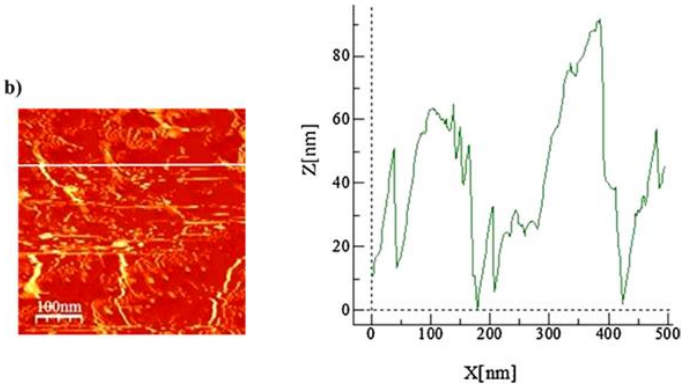


Fig. 17 – AFM images of laser treated surface: (a) 3-dimensional view of laser treated surface, (b) imaged use for surface roughness, and (c) surface roughness along the line shown in the image.

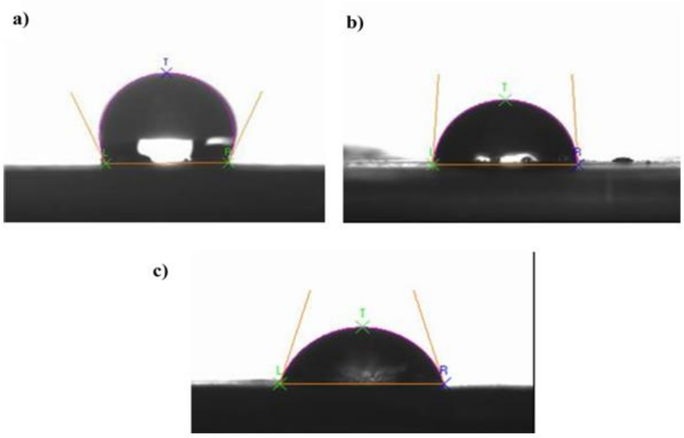


Fig. 18 – Optical images used for contact angle measurements, (a) 125◦contact angle at the laser treated surface, (b) 86.5◦contact angle at the laser treated surface, and (c) 68.4◦contact angle at the untreated surface.

In the study of the influence of processing parameters on the wettability of PTFE, it was demonstrated that higher laser power increases the contact angle due to increased roughness (Fig. 19). The treated surfaces exhibited high chemical and mechanical resistance, making them suitable for self-cleaning applications (Riveiro *et al*., 2020), while for the PVD polymer, the "lotus" effect was observed, where the contact angle increased from 65° to 110° (Choi *et al*., 2021). Another analysis focused on modifying the roughness and wettability of thin films of poly(L-lactic acid) (PLLA) through CO_2 laser irradiation, observing an increase in microstructures and variation in wettability (Figs. 20 and 21), (Tomanik *et al*., 2020).

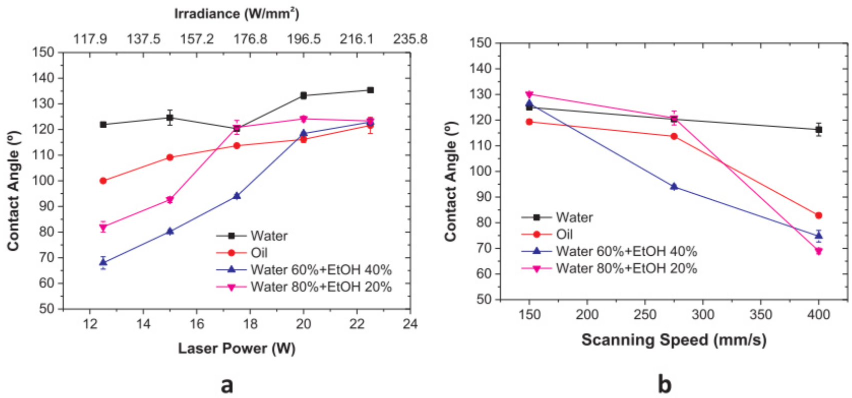


Fig. 19 – Influence of the laser power (Processing conditions: Δx = 0.250 mm, v = 275 mm/s) and scanning speed (Processing conditions: P = 17.5 W, Δx = 0.250 mm) on the contact angle using: water, oil, Water 60%+EtOH 40%, Water 80%+EtOH 20% as test fluids.

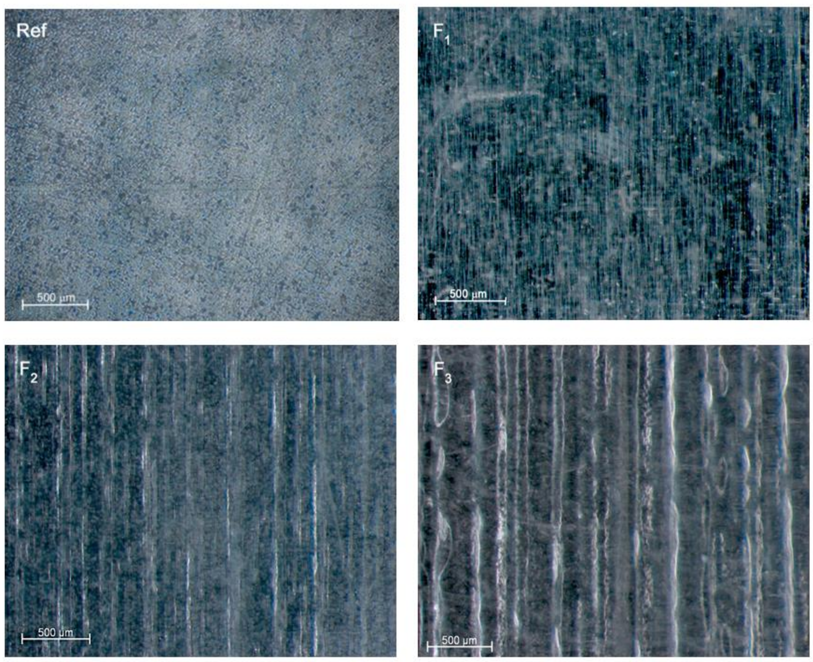


Fig. 20 – Microscopic images of the obtained surfaces (magnification 100×) recorded for the reference material (Ref) and laser-treated with cumulative fluences of 24 J/cm² (F1), 48 J/cm² (F2), and 71 J/cm² (F3).

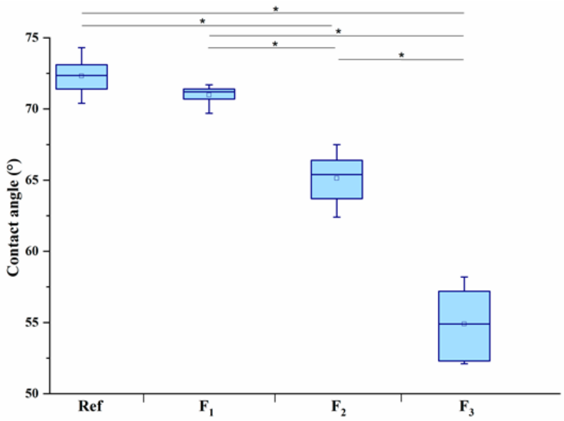


Fig. 21 – Surface wetness modified with different laser parameters; statistical significance between study groups for water and PBS, obtained through one-way ANOVA and post-hoc Tukey tests.

Singh *et al.* (2021) investigated the influence of laser texturing on the wettability and antibacterial properties of metallic, ceramic, and polymeric materials, demonstrating that triangular microtextures reduce hydrophilicity and bacterial density (Fig. 22). Meanwhile, Mazurchevici *et al.* (2023) studied the laser texturing of the biodegradable material Arboblend V2 Nature, highlighting the impact of geometries on the contact angle (Fig. 23). Other studies (Ghadiri Zahrani *et al.*, 2024) used femtosecond lasers to generate spherical and pyramidal textures on polymers, influencing their hydrophobic properties (Fig. 24).

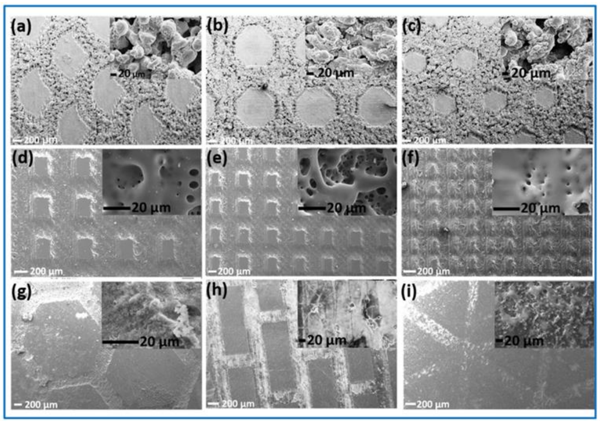


Fig. 22 – SEM images of Ti–6Al–4V: (a) fishscale, (b) octagonal, and (c) hexagonal features, and textured PMMA: (d) large, € medium, and (f) small rectangular features, and textured HAp: (g) hexagonal, (h) brick, and (i) triangular features.

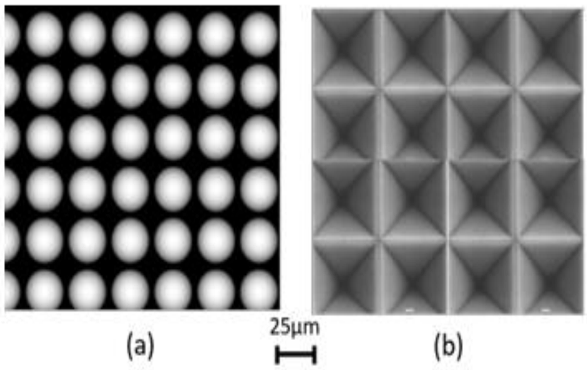


Fig. 23 – Patterns used for laser texturing:
(a) Ball and (b) Pyramid

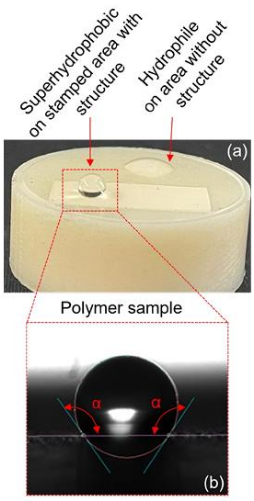


Fig. 24 – (a) Comparison between hydrophobic and hydrophile areas and (b)Measurement of contact angle.

3. Conclusions

Laser surface texturing represents a versatile and powerful method for tailoring the properties of biodegradable polymer surfaces. By precisely controlling the laser parameters, significant improvements in mechanical strength, friction reduction, thermal stability, and wettability can be achieved. The reviewed studies highlight that while moderate laser fluences enhance hardness and reduce friction, excessive fluence may lead to undesirable degradation. Furthermore, the ability to modify surface wettability–ranging from superhydrophilic to superhydrophobic states–opens new avenues in self-cleaning materials and biomedical applications. Future research should focus on further optimizing processing parameters and evaluating long-term performance under operational conditions.

The presented results validate the remarkable potential of Laser Surface Texturing (LST) for the controlled modification of the mechanical properties of polymers, offering the possibility of fine-tuning surface characteristics for specific functional applications. The evident benefits in reducing wear and enhancing surface durability position LST as a viable technological solution for optimizing material performance under demanding industrial conditions.

Moreover, LST's ability to regulate wettability through the manipulation of surface roughness and microstructures opens significant prospects in emerging fields such as advanced materials, self-cleaning surface technologies, and biomedical engineering.

Thus, there is a clear need for continued research to expand the applicability of this technique by optimizing process parameters and exploring its interaction with new classes of materials, in order to fully harness its industrial and scientific potential.

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CARACTERIZAREA SUPRAFEȚELOR TEXTURATE CU LASER – O REVIZUIRE

(Rezumat)

Texturarea suprafețelor cu laser (LST) reprezintă o tehnică avansată și extrem de versatilă pentru modificarea proprietăților suprafețelor biopolimerice, cu aplicații largi în domeniile biomedical, auto și industrial. Această lucrare de sinteză investighează influența LST asupra proprietăților mecanice, tribologice, termice și de umectabilitate ale suprafețelor polimerice și biopolimerice, având ca scop principal îmbunătățirea performanței și durabilității acestora. Metodologia se bazează pe utilizarea ablației laser pentru a genera microstructuri cu diverse geometrii, prin optimizarea parametrilor de procesare esențiali precum fluenta laserului, viteza de scanare și durata pulsului. Studiul

include o gamă variată de materiale, printre care PLA, PHA, PEEK, HDPE și PET, analizând modul în care acestea răspund la modificările induse de texturarea cu laser. Investigațiile experimentale includ teste mecanice (microduritate, rezistență la tracțiune), evaluări tribologice (coeficient de frecare, rezistență la uzură), analize termice (DSC, TGA) şi măsurători de unghi de contact pentru evaluarea umectabilității. În plus, se analizează impactul diferitelor modele de texturare – cum ar fi structurile liniare, hexagonale și circulare – asupra comportamentului materialelor.

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THE INFLUENCE OF FDM TECHNOLOGY PARAMETERS UPON PRINTING ONTO TEXTILE SUBSTRATES

BY

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Abstract. The integration of additive manufacturing into textile and fashion engineering has enabled the development of hybrid material systems and novel fabrication strategies. Among the various 3D printing technologies, Fused Deposition Modeling (FDM) is widely utilized due to its accessibility, material compatibility, and the extensive control it offers over process parameters. While prior research has primarily focused on optimizing interlayer bonding and structural performance in conventional FDM applications, the direct deposition of polymers onto textile substrates introduces a distinct set of challenges, particularly in achieving reliable adhesion to flexible, porous surfaces. Existing literature has predominantly examined this issue from the perspective of textile properties–such as weave structure, fiber composition, and surface topography–while considerably fewer studies have addressed the role of printing parameters. This review consolidates and critically evaluates current research that investigates the influence of FDM process settings–including nozzle and bed temperature, nozzle-to-substrate distance, print speed, flow rate, and cooling conditions–on the adhesion performance of polymer–textile interfaces. The review aims to identify recurring trends, highlight unresolved challenges, and outline promising directions for future investigations in this rapidly evolving area.

Keywords: 3D printing; settings; parameters; adhesion; textiles; fabric.

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1. Introduction

Over the past decade, Fused Deposition Modeling (FDM) 3D printing has evolved from a prototyping tool into a widely used method for manufacturing, driven by advancements in materials, hardware, and slicing software. Standard parameters for materials like PLA–such as nozzle temperatures between 190°C and 215°C, bed temperatures around 60°C, and print speeds of 30–50 mm/s–have proven effective for achieving good interlayer bonding and surface quality in conventional applications. However, in the emerging field of 3D printing directly onto textiles, these default settings require reconsideration.

The integration of 3D printing onto textile substrates offers significant opportunities for innovation in fashion, functional apparel, and technical textiles, enabling the creation of hybrid materials with enhanced properties and custom functionalities. This integration facilitates advanced applications including sensor integration and the use of conductive polymers, enabling garments to sense environmental stimuli, monitor physiological conditions, and transmit data. Additionally, mechanical functionalities such as articulated joints, flexible structures, and adaptive support elements can be integrated directly onto textiles, significantly enhancing their practical utility and ergonomic performance. Successfully addressing adhesion challenges between polymers and textiles is critical to harnessing these opportunities. Improved adhesion ensures greater durability, wash resistance, and performance consistency of printed structures, thereby expanding their practical applications. Achieving reliable polymer-textile bonding not only enhances the mechanical and aesthetic qualities of composite materials but also fosters sustainability by enabling the creation of more durable and versatile products.

Extended research in this area has primarily focused on how textile-related factors–such as yarn composition, weave density, thickness, and porosity–affect adhesion (Sheron *et al.*, 2018; Čuk *et al.*, 2020; Kočevar, 2023). While this has generated valuable insights, printer-side parameters that can be directly controlled during the manufacturing process have received comparatively less attention. As polymer–textile adhesion is a complex phenomenon involving mechanical interlocking, thermal dynamics, and surface compatibility, printer settings may play a critical role in achieving reliable and durable bonding.

This review aims to synthesize recent studies that deliberately varied FDM printing parameters to improve adhesion between polymer and textile substrates. The focus is placed on parameters such as nozzle temperature, bed temperature, Z-distance, flow rate, and first-layer print settings. Additionally, the review highlights underexplored variables–including cooling fan control and print speed modulation–that may significantly impact first-layer behavior. By mapping the current landscape of research and identifying consistent findings, contradictions, and methodological gaps, this work seeks to provide a foundation for further innovation in textile-integrated 3D printing.

1.1. Methodology of Literature Selection

This review focuses on identifying and analyzing studies that investigate the influence of Fused Deposition Modeling (FDM) printing parameters on adhesion to textile substrates. The literature selection was conducted based on a targeted search of publications from the period 2016 to 2023. Three primary sources were used to retrieve relevant articles: ScienceDirect, ResearchGate, and reference tracing from highly cited and thematically related publications.

Keyword combinations such as "*3D printing fabric*", "*3D printing textiles*", and "*FDM adhesion*" were used to locate studies specifically addressing the interaction between polymer deposition and textile surfaces. Studies that focused on other additive manufacturing technologies (e.g., SLA, SLS) or on textile property analysis without reference to printer settings were excluded from the core review.

In total, approximately 48 papers related to 3D printing on textiles were screened. Of these, 18 studies that explicitly investigated the effect of printer-side parameters–such as extrusion temperature, bed temperature, Z-offset, print speed, and flow rate–on polymer–textile adhesion were selected for in-depth analysis. Additional references focused on textile characterization are mentioned briefly in the introduction to provide context but are not central to the technical synthesis.

2. FDM Printing Parameters and Methods Influencing Adhesion

A standard slicer such as Cura or Orca Slicer allows adjustment of dozens of parameters related to material extrusion, movement, and thermal control. Despite the wide range of adjustable variables, only a limited number have been specifically identified as having a direct impact on adhesion to textile substrates. Most studies have focused on a few key parameters–such as speed, nozzle temperature, bed temperature, Z-distance, and first layer orientation–while many others remain unexplored in this context.

Due to the wide variation in experimental designs, material combinations, and adhesion test methods across the reviewed studies, direct quantitative comparisons between parameter effects are not feasible. For this reason, no unified table summarizing numerical outcomes is included, as such a synthesis would risk misrepresenting the underlying methodological inconsistencies. Instead, qualitative patterns and parameter sensitivities are discussed contextually within each subsection.

2.1. Main parameters (Z-distance, printing speed, nozzle and build plate temperature)

Döpke *et al.* (2016) investigated the adhesion of PLA to knitted textile substrates, representing one of the earliest studies to vary printer settings to improve adhesion. The study found that z-distance–the nozzle-to-surface gap–directly influenced adhesion, likely due to the pressure exerted by the molten polymer as it infiltrates the textile structure. Nozzle diameter was also varied between 0.4 mm and 1 mm, with larger diameters showing a positive correlation with adhesion strength. In contrast, flow rate and bed temperature were reported to have minimal influence on adhesion in the tested conditions. As depicted in Fig. 1 adhesion forces were measured for PLA prints produced with varying nozzle diameters.

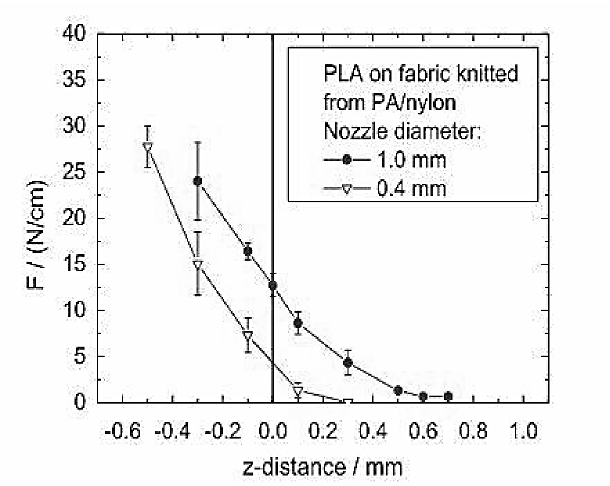

Fig. 1 – Adhesion forces, measured between PLA prints with different nozzle diameters at different z-distances (source: Döpke *et al.*, 2016).

Spahiu *et al*. (2017) examined the influence of various printer settings on polymer–textile adhesion. Reducing the print speed from 37.5 mm/s to 22.5 mm/s led to a slight improvement in adhesion. Increasing the extrusion temperature from 200°C to 220°C resulted in a more substantial improvement, attributed to the lower viscosity of the molten polymer.

Consistent with previous findings, flow rate showed no significant effect. Bed temperature, however, had the most pronounced impact: raising it from ambient (20°C) to 60°C and 100°C greatly improved adhesion by allowing PLA to remain fluid longer and penetrate the textile structure. However, at 100°C, irregular deformation of the print was observed, likely due to prolonged overheating. Z-distance was also varied and found to significantly affect adhesion, in line with earlier studies. Illustrated in Fig. 2, from left to right, are the influences on the adhesion of printing speed, nozzle temperature, bed temperature and flow rate. Wash tests at 40°C did not reveal notable changes in adhesion performance.

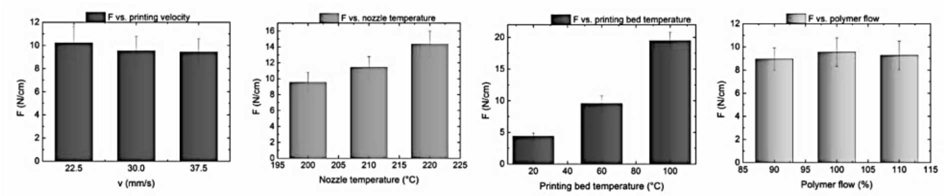

Fig. 2 – Influences on the adhesion of printing speed, nozzle temperature, bed temperature and flow rate (source: Spahiu *et al.*, 2017).

Rivera *et al.* (2017) explored various applications and functionalities of direct 3D printing onto textile surfaces. Fig. 3 illustrates how simple segments of straight plastic with a bend angle and a channel built in, can be transformed into a roll by pulling a string through the channel.

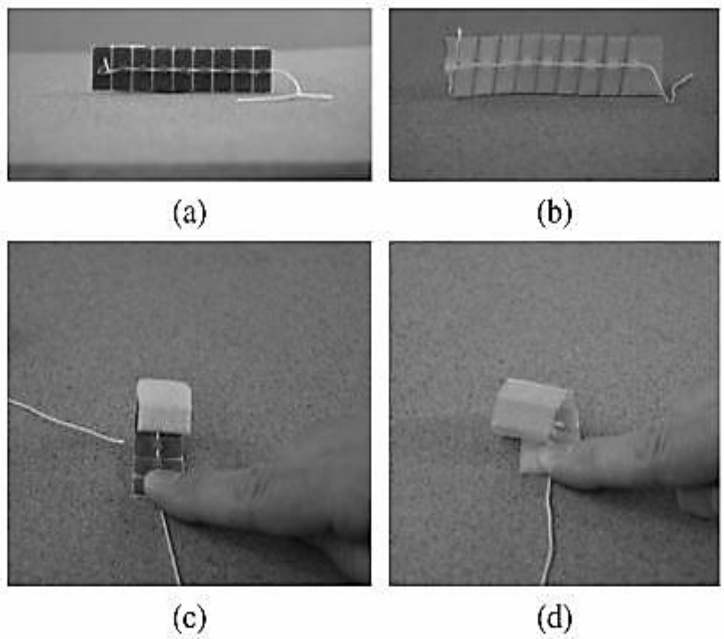

Fig. 3 – Example of a rolling functionality (source: Rivera *et al.*, 2017).

Adhesion strength was evaluated using an Instron Model 5567 tensile testing machine to measure the force required to detach the printed polymer from the fabric (Fig. 4). The results indicated that textile type, print geometry, and printer settings significantly affect the degree of adhesion between the materials.

Fig. 4 – Adhesion testing assembly (source: Rivera *et al*., 2017).

The study also highlighted technical challenges, including difficulties in securing the fabric to the print bed and its behavior during printing (Fig. 5). Additional limitations were noted regarding the long-term durability of the combined materials, due to interactions between the rigid polymer and the flexible textile, as well as constraints imposed by the limited build volume when printing larger objects.

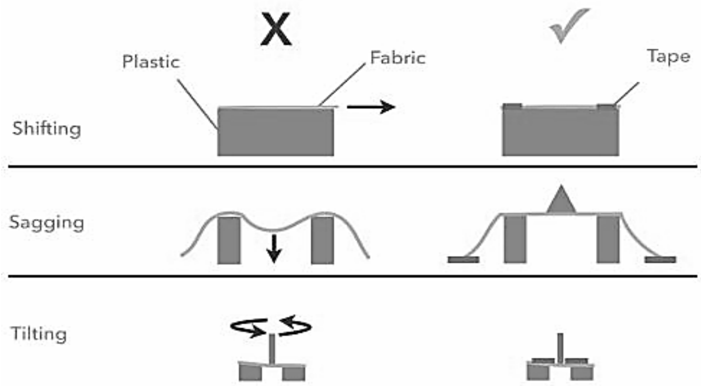

Fig. 5 – Different problems and solutions when printing on textiles (source: Rivera *et al*., 2017).

Hashemi Sanatgar *et al.* (2017) also demonstrated that extruder temperature and print speed have a significant impact on polymer–textile adhesion strength. In contrast, bed temperature was found to be relevant only when it exceeded the glass transition temperature of the textile substrate.

Eutionnat-Diffo *et al.* (2018) highlights the potential of using FDM for smart textile manufacturing, showing that platform temperature, heat transfer, and the structural properties of both polyester fabrics and PLA filament influence adhesion. Achieving optimal adhesion may require adjusting FDM parameters based on the textile substrate or modifying the textile itself. However, challenges remain in ensuring process repeatability across different fabric types due to variations in thermal behavior and structure.

Spahiu *et al.* (2018) examined the influence of Z-distance, bed temperature, identified as the most critical variables. The results indicated that higher bed and nozzle temperatures, combined with a reduced Z-distance (above the nozzle clogging risk threshold), significantly improved adhesion. It was also observed that Z-distance could be increased at elevated temperatures to compensate for thermal expansion of the bed and filament within the nozzle. Additionally, variations in substrate compressibility were noted, suggesting a potential influence on adhesion. While this aspect was not explored in depth within the study. It was later addressed by Meyer *et al*. (2019) which emphasized the importance of optimizing Z-distance, not only based on fabric thickness but also considering the compressibility of the textile substrate.

Eutionnat-Diffo *et al.* (2020b) evaluated the influence of build platform temperature, textile structure, and thermal transfer on the adhesion and wash durability of 3D printed PLA layers on PET fabrics. The results indicated that increased surface roughness, higher porosity, and lower thermal conductivity of the textile substrate enhance adhesion. Platform temperature exhibited a quadratic effect on bonding strength. Although adhesion was reduced by approximately 50% after washing, more porous and rougher textile structures contributed to improved durability of the printed layers.

Kozior *et al.* (2020) reviewed existing literature on 3D printed polymer adhesion to textile substrates, identifying several key 3D printing parameters that influence bonding. The study emphasized that low polymer viscosity and high pressure can promote penetration into the fabric, enhancing mechanical interlocking. Pressure was noted to be closely related to Z-distance and affected by the extrusion temperature. Additionally, the authors pointed out that some parameters commonly studied in inter-layer adhesion–such as print speed–have not been thoroughly investigated in the context of textile printing and remain inconclusive in current literature.

Mpofu *et al.* (2020) demonstrated that 3D printing parameters influence the mechanical and adhesive properties of PLA/textile composites. Extrusion temperature, printing speed, and model height were identified as key factors affecting adhesion (Fig. 6), both before and after washing, whereas infill density had no significant impact by itself. Adhesion force was positively correlated with extrusion temperature and negatively correlated with both printing speed and model height. Washing reduced adhesion in all cases. Similarly, tensile strength increased with temperature and decreased with higher printing speed and model height.

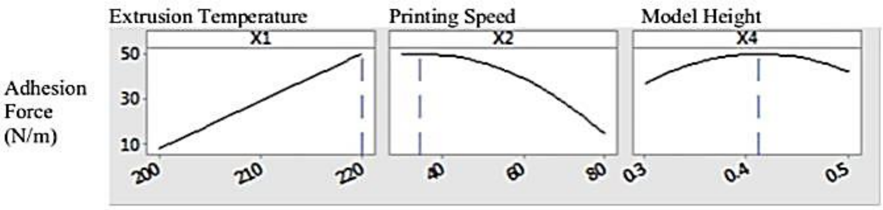

Fig. 6 – Key factors affecting adhesion (source: Mpofu *et al*., 2020).

2.2. Additional parameters (infill pattern, angle and density)

In 3D printing, the infill refers to the internal structure of a printed object, typically composed of a repeated geometric pattern that fills the space between the outer walls (or shells). Its primary function is to provide internal support and influence mechanical properties such as strength, weight, and material consumption. Infill patterns, density, and orientation are customizable and are generally not visible from the outside of the object. Importantly, the infill does not normally come into contact with the build platform or substrate, as it is enclosed by the bottom and top solid layers. Therefore, under standard conditions, infill parameters would not directly affect adhesion to the textile substrate as mentioned by Mpofu *et al.* (2020) in their findings.

However, in some studies, researchers intentionally removed the bottom layers to print directly with the infill structure, in order to be able to change parameters such as pattern, angle and density–settings that were only accessible for infill and not for bottom layers in the slicing software. As a result, findings based on these modified setups may incorrectly attribute adhesion effects to infill properties rather than to the altered behavior of the first printed layer.

Kozior *et al*. (2018) investigated the influence of textile pretreatments and infill orientation on the adhesion strength of PLA printed directly onto cotton fabric. The tests showed that a 90° infill orientation resulted in the highest adhesion, while orientations of 0° and above 90° led to reduced bonding (Fig. 7).

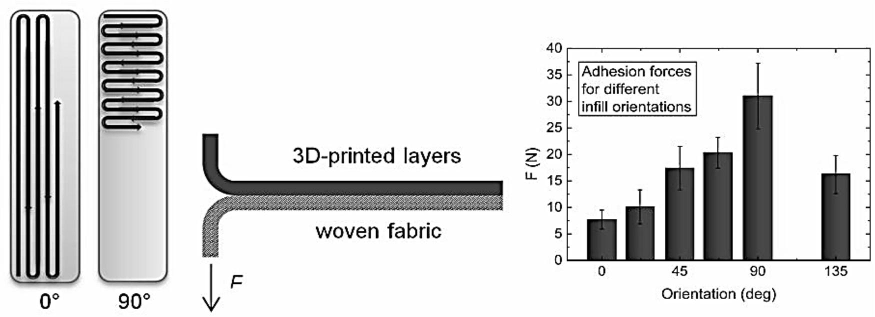

Fig. 7 – Correlation between first layer orientation and adhesion
(source: Kozior *et al*., 2018).

Redondo *et al.* (2020) investigated the influence of print angle on the adhesion of 3D printed PLA onto cotton fabric substrates, varying its orientation between 45°, 90°, and 180°. Peel tests revealed that printing at a 45° angle resulted in the strongest adhesion.

Singh *et al*. (2021) also investigated the effect of infill type and density on the adhesion between 3D printed material and textile substrates. The study concluded that increasing the infill percentage enhances the adhesive bonding between the printed polymer and the fabric surface. Fig. 8 illustrates two test samples being printed with honeycomb infill pattern in two different densities.

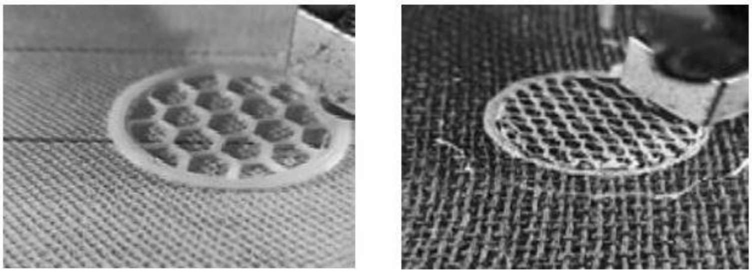

Fig. 8 – Honeycomb pattern in two different densities
(source: Singh *et al*., 2021).

2.3. Testing methods

In the literature, a significant number of researchers have measured adhesion using the T-peel test method. This approach involves printing a thin polymer layer, which bends during testing.

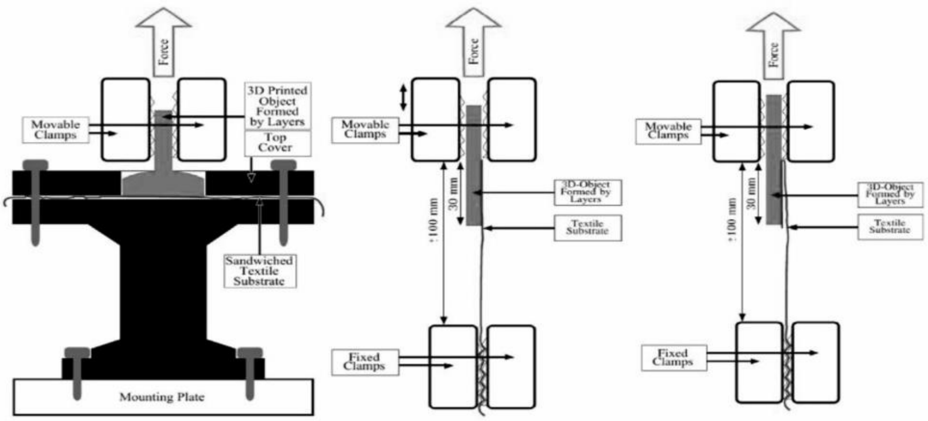

Fig. 9 – Perpendicular tensile test, shear test, and peel test
(source: Malengier *et al*., 2018).

However, except in cases where the polymer is soft or elastic, bending rigid polymers often results in deformation or fracture–either of the polymer or the textile substrate–potentially compromising the accuracy of the results. Malengier *et al*. (2018) presents three proper methods for evaluating adhesion and their properties: (A) perpendicular tensile test, (B) shear test, and (C) peel test (Fig. 9). The shear and peel methods treat the polymer as a solid material and involve printing thicker test pieces to reduce deformation. Despite this adjustment, both methods frequently led to tearing of the textile substrate during testing. The study concluded that the perpendicular tensile test is the most appropriate method for assessing adhesion, as it minimizes the risk of damaging the fabric. In this configuration, the polymer is pulled vertically–along the same direction it infiltrated the textile–without exerting significant lateral stress on the fabric structure.

2.4. Additional Findings in the Literature: TPU, Conductive Materials, and Alternative Approaches

Özev and Ehrmann (2023) investigated the integration of cotton and aramid fabrics into 3D printed structures. Unlike most studies that focus on achieving surface adhesion between the printed material and the textile, this research explored the embedding of fabrics within internal cavities of the print–an approach relevant for stab resistant clothing applications. Small protrusions were designed within the 3D printed structure to secure the fabric in place and prevent vertical displacement. Both PLA and TPU were tested, with TPU yielding promising results despite its higher printing complexity at the time. The integrated protrusions effectively held the textiles in place, showing no fabric movement even after repeated bending tests.

Cakar and Ehrmann (2023) investigated the stab resistance properties of three TPU filaments with different hardness levels (Shore 98A, 85A, and 82A) printed onto viscose fabric. The results showed that the highest adhesion was achieved with the softest filament, TPU 82A, while TPU 85A and 98A demonstrated superior performance in stab resistance tests. These findings suggest a potential multi-material strategy, in which a soft TPU layer (82A) is used as the initial layer to enhance adhesion, followed by harder TPU layers to provide increased stab resistance.

Eutionnat-Diffo *et al.* (2020a) investigated the abrasion resistance of 3D-printed polymer-on-textile (3D-PPOT) materials fabricated via Fused Deposition Modeling (FDM). The study found that weave type, weft density, and platform temperature were the most influential factors affecting both weight loss and wear endpoint. In contrast, the printing direction had no effect on abrasion resistance. Optimal performance was achieved using plain weave fabrics with the highest weft density and the lowest bed temperature. While porous and rough textile substrates improved adhesion between the printed polymer and the fabric, they negatively impacted abrasion resistance. The 3D-printed conductive PLA materials exhibited greater structural compactness, lower porosity, and enhanced fiber cohesion, resulting in higher abrasion resistance and reduced material loss compared to unprinted fabrics. However, abrasion significantly impaired the electrical conductivity of the printed conductive layer.

One of the most innovative studies to strategically exploit printer settings is that of Forman *et al.* (2020), who developed "DefeXtiles"–a material that mimics woven textiles not through traditional pillar structures, but by harnessing under-extrusion, typically considered a 3D printing defect. By deliberately reducing the flow rate from the standard 95–100% to 30–50%, the researchers achieved thin, lightweight, flexible sheets with intermittent bonding that created a woven-like appearance. This work demonstrated how precise control of extrusion parameters can turn a printing flaw into a functional design strategy, enabling the creation of textile-like materials without the need for supports or assembly.

2.5. Limitations and Directions for Future Research

One of the most significant limitations in the current body of research on FDM printing onto textile substrates is the absence of standardized testing protocols for evaluating polymer–fabric adhesion. Various studies employ different methods–such as T-peel, shear, or tensile tests–often with custom geometries, material combinations, and sample preparation procedures. This lack of methodological uniformity makes direct comparisons between studies problematic, limiting the ability to isolate and quantify the individual impact of specific printing parameters across the literature. As a result, it is currently difficult to construct a cohesive framework or set of best practices based solely on the data available. Establishing standardized testing conditions, including sample size, fabric type, print geometry, and load application method, would represent a major step forward for the reproducibility and comparability of results in this field.

In addition, a critical yet often overlooked parameter in the reviewed literature is the cooling fan operation, particularly during the first layer of the print. Only a limited number of studies explicitly state whether the part cooling fan was enabled or disabled, and it is likely that its status varied unintentionally between experiments depending on slicer defaults. This oversight is significant, as active cooling can substantially reduce the surface temperature of the extruded polymer, potentially limiting its ability to bond effectively with the textile substrate. Since adhesion relies heavily on thermal interdiffusion and partial infiltration of the polymer into the porous fabric, maintaining an elevated temperature during the first layer is critical. Future research should systematically investigate the role of cooling fan control–both in terms of on/off status and fan speed–and its interaction with other thermal parameters such as nozzle and bed temperature, in order to fully understand its impact on adhesion performance.

Another promising yet underexplored direction in the context of FDM printing onto textiles is the use of multi-layer or multi-material strategies to enhance adhesion and functional performance. While a few studies have begun to investigate the sequential deposition of different thermoplastic materials–such as a soft initial layer for improved bonding followed by harder layers for structural reinforcement (Cakar and Ehrmann, 2023) –systematic research in this area remains limited. Layered material approaches may enable a more controlled balance between flexibility, durability, and adhesion strength, particularly in wearable applications that require both comfort and resistance to mechanical stress. Further investigations are needed to assess the interfacial behavior between dissimilar materials when printed onto fabrics, as well as the long-term durability of such composites under repeated bending, abrasion, and washing cycles. Incorporating gradient materials or interface-optimized transition zones could represent a significant advancement in the design of textile–polymer hybrid systems.

3. Conclusions

This review has highlighted that adhesion between FDM-printed polymers and textile substrates is highly sensitive to a small set of printer-side parameters, particularly those affecting the first printed layer. Variables such as nozzle temperature, bed temperature, Z-offset, and print speed have consistently shown significant influence over interfacial bonding. When carefully adjusted, these settings can enhance polymer flow, promote mechanical interlocking, and improve overall adhesion quality.

Although the reviewed studies provide valuable insights, direct comparisons remain challenging due to divergent methodologies and experimental setups. Nevertheless, the consistent appearance of key trends across independent research efforts reinforces the importance of printer-controlled variables in textile-integrated additive manufacturing.

By consolidating current findings, this work contributes to a more coherent understanding of parameter influence in FDM-textile systems and lays the groundwork for more systematic and reproducible future studies in this field.

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INFLUENȚA PARAMETRILOR TEHNOLOGIEI FDM ASUPRA IMPRIMĂRII PE SUBSTRATURI TEXTILE

(Rezumat)

Integrarea fabricației aditive în ingineria textilelor și a modei a permis dezvoltarea unor sisteme de materiale hibride și a unor noi strategii de fabricație. Dintre diferitele tehnologii de imprimare 3D, Fused Deposition Modeling (FDM) este utilizată pe scară largă datorită accesibilității sale, compatibilității materialelor și controlului extins pe care îl oferă asupra parametrilor procesului. În timp ce cercetările anterioare s-au axat în principal pe optimizarea aderenței între straturi și a performanței structurale în aplicațiile FDM convenționale, depunerea directă de polimeri pe substraturi textile introduce un set distinct de provocări, în special în ceea ce privește obținerea unei aderențe fiabile la suprafețele flexibile și poroase. Literatura de specialitate existentă a examinat această problemă în principal din perspectiva proprietăților materialelor textile - cum ar fi structura țesăturii, compoziția fibrelor și topografia suprafeței - în timp ce mult mai puține studii au abordat rolul parametrilor de imprimare. Această analiză consolidează și evaluează critic cercetările actuale care investighează influența parametrilor procesului FDM - inclusiv temperatura duzei și a patului, distanța dintre duză și substrat, viteza de imprimare, rata de extrudare și condițiile de răcire - asupra performanței de aderență a interfețelor polimer-textil. Această revizuire urmărește să identifice tendințele recurente, să evidențieze provocările nerezolvate și să contureze direcții promițătoare pentru cercetările viitoare în acest domeniu care evoluează rapid.

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ADVANCED TITANIUM ALLOYS FOR MEDICAL AND INDUSTRIAL USE

BY

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Abstract. This article aims to discuss ways of improving the properties of titanium alloys, exploring various strategies to enhance strength of the material, the corrosion resistance and most importantly the biocompatibility, meaning a particular focus on mechanical performance, structural integrity, and biocompatibility, suited for orthopaedic and dental implants. It examines the effects of different alloying elements and the impact titanium's phases have on these properties. Additionally, the paper discusses production methods ranging from extraction to surface treatments and includes structural characterization techniques, such as mechanical testing, corrosion resistance evaluation, and microstructure analysis. Titanium and its alloys are highly valued for their strength-to-weight ratio, exceptional corrosion resistance, flexibility, and biocompatibility, making them suitable for a diverse array of applications, which will be detailed further in this work. Future directions emphasize the use of 3D engineering for the development of customized implants, surface modifications to enhance biocompatibility, and the exploration of biodegradable alloys.

Keywords: Titanium Alloys, Biomaterials, Medical Devices, Alloy Characterization, Biocompatibility, Mechanical Testing, Alloying Elements.

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1. Introduction

Biomaterials are synthetic materials whose function is to replace a living part or a system and also interact and diagnose possible problems with living tissues. Not every artificial material that comes into contact with the skin is part of the biomaterials category, only the materials that replace human organs, parts of them, or systems that lost their function to improve the functions and speed up the recovery process (Detsch *et al*., 2018).

The scientific branch of biomaterials grew larger thanks to the continuous development and research in medicine, providing an alternative method for accelerating the recovery process or assisting the healing of human health problems (Vallet-Regi, 2022).

Biomaterials are a class of special materials used in contact with biological tissues, whose purpose is treating, modifying, or replacing an organ or the functions of the organism, altogether making it possible to observe them.

Biomaterials have specific needs based on their function. However, the main ones are compatibility, which means being able to work with living tissue and not wearing down easily; mechanical properties, like having a certain elastic modulus, being flexible, and not breaking down easily under stress; and corrosion resistance (Najafizadeh *et al*., 2024).

Biomaterials have different purposes, based on the needs of the organism alongside which they function or to replace; examples are contact lenses, dental implants and teeth braces, catheters, finger and knee joint implants, knee and hip replacement, bone cement and plates, synthetic ligaments and tendons, synthetic skin and skin repair devices, heart valves, and hearing aids (Eliaz, 2019).

This paper focuses on biomaterials obtained from processed metals (Fig. 1), such as titanium and its alloys. To further emphasize, the great properties of titanium and the enhanced properties of its alloys, such as mechanical strength, durability, biocompatibility, corrosion resistance, and osseointegration, make it more than suited for biomedical applications (Niinomi and Boehlert, 2015).

The main raw materials used in the creation of biomaterials are metals, polymers, ceramics, and composite materials.

Metals are incredibly hard materials with high density and a good elastic modulus; the problems occur in time, since metallic materials can corrode. Another common problem is the high density, which not only increases the weight of the material, but could also create problems during the removal process (Wang *et al*., 2021).

Tissue engineering, drug delivery systems, and wound care primarily utilize polymers due to their elastic modulus and ease of manufacture. The polymers can be biodegradable and non-biodegradable, in which case the fact that substances are not durable could be an advantage or a disadvantage depending on their use; they can also deform under stress, creating problems.

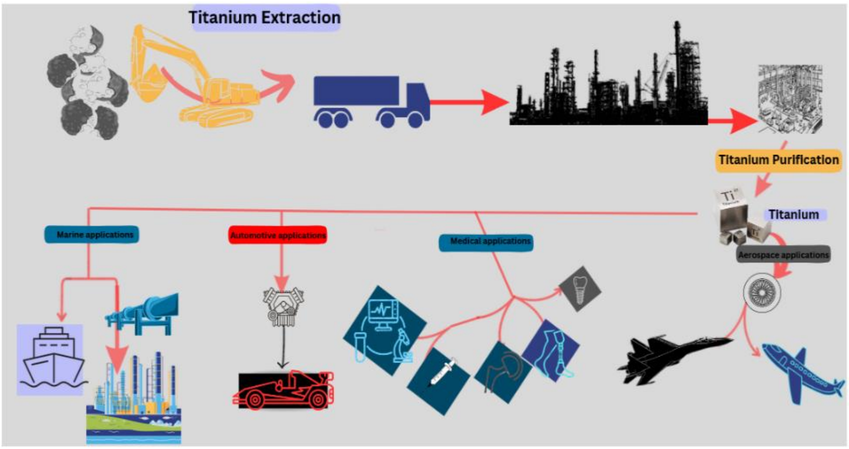

Fig. 1 – Graphical abstract.

Ceramics have a range of applications, especially in orthopedics and dentistry; however, they have certain limitations. Although they have excellent biocompatibility–osteoconductive and low toxicity–and are inert, ceramics are also fragile; they can crumble, are quite difficult to obtain, and are limited in use due to the fact they have no elastic modulus (Shanmugam and Sahadevan, 2018).

Composite materials are a combination of materials whose properties can both be employed together, such as the strength of metals and biocompatibility of ceramics. Based on the materials combined, they usually have enhanced mechanical properties like strength and toughness, improved biocompatibility, wear resistance, customization, and improved processability.

Although composite materials are made with targeted properties, they have Biomaterials are a special class of materials whose purpose is the direct interaction with biological systems with the intention of repairing damaged tissues, replacing certain body parts, or aiding in their recovery (Egbo, 2021). Table 1 presents a brief classification of biomaterials and their respective uses (Baltatu *et al*., 2019b; Raut e*t al*., 2020).

Table 1
Classification of biomaterials and uses

Material type	Biomedical applications
METALS: Titanium alloys, Stainless steel, Co-Cr Alloys, Gold (Au)	Prostheses, bone plates and screws, dental implants, hip and knee joints
POLYMERS: Nylon, Silicone, Teflon, Dacron	Surgical sutures, blood vessels, joints, synthetic skin, soft tissues
CERAMICS: Aluminium Oxide, Carbon Hydroxyapatite, Zirconia (ZrO_2), Ceramic Glass	Dental alveoli, hip joints
COMPOSITES: Carbon-Carbon	Joints and heart valves

Biomaterials are defined by certain characteristics, such as their mechanical properties, microstructural properties, chemical properties, and biocompatibility (Kiran *et al.*, 2021).

Biocompatibility is a property that allows biomaterials to interact with human tissues, organs, or cells without creating any risk or adverse reactions–a key factor that ensures that no toxic reactions can occur and promotes healing or integration in the organism or living system.

The mechanical properties are strength, elasticity, hardness, and fatigue resistance–these are variable properties since biomaterials serve different purposes, while overall it is important to have a resistant material that can withstand all; some biomaterials are especially designed to degrade, e.g., polymers, hydroxyapatite.

The purpose of the chemical properties, chemical stability and corrosion resistance, is to prevent degradation due to errosion or unwanted chemical reactions.

Surface properties present in biomaterials are hydrophilicity or hydrophobicity, as well as roughness and porosity.

Although biomaterials come in various forms and from various materials, metals have always been the go-to in this field, thanks to their durability, strength, long-term performance, strength-to-weight ratio, wear, and stress resistance.

In the biomedical field, metals are excellent picks when it comes to orthopedic implants, dental implants, and cardiovascular implants.

Alongside the benefits the mechanical properties bring, the chemical properties of metals are also important, such as the corrosion resistance, prolonging the life of the material and reducing the risk factor.

When it comes to metals, one of the most commonly used is titanium, due to its unique set of characteristics and uses, such as orthopedic prostheses, dental implants, stents, bone plates, screws, and joint replacement.

Important characteristics of titanium are biocompatibility and corrosion resistance; titanium is highly biocompatible, and its surface builds a layer of titanium oxide (TiO_2), furthering its resistance to corrosion.

Titanium also exhibits low thermal conductivity, making it a perfect choice for medical implants that are near or in contact with sensitive tissues and organs, preventing heat transfer, and minimizing the risk of tissue damage.

The importance of titanium is also given by the wear resistance and, more importantly, the ability to encourage osseointegration, which is useful for bone screws and plates and dental implants (Marin and Lanzutti, 2023).

One other benefit titanium has is the ease of manufacture; although at a high price, titanium can be molded and shaped precisely for the device or prosthesis required, coupled with possible surface treatments such as coatings, it can create more durable or porous surfaces to fit the needs.

2. Classification of Titanium Alloys

As previously stated, biomaterials are synthetic materials designed to interact with biological systems to treat, repair, or replace damaged tissues and organs. Among various biomaterials, titanium and especially titanium alloys stand out thanks to their properties. Titanium alloys are widely used in medical applications, such as orthopedics, dentistry, and cardiovascular devices (Wang *et al*., 2021).

Titanium is highly suited for the body; the most important properties for its use in medical applications are:

• **Biocompatibility:** this trait means that titanium does not cause adverse reactions when in contact with human tissues and organs. Titanium also bonds with the bone tissue, further favoring its usage for implants. One other key factor of titanium when it comes to biocompatibility is the oxide layer that it naturally forms when exposed to oxygen, making it more stable and preventing the immune system of the body from attacking the implants (Gobbi *et al*., 2019).

• **Corrosion resistance:** a property evident even in aggressive environments, such as body fluids. The resistance is given thanks to the stable oxide layer on its surface, making titanium particularly suited for biomedical applications, where resistance to moisture, salts, and other elements is a must (Eliaz, 2019).

• **Strength-to-weight ratio:** titanium, being stronger than other metals yet lighter than stainless steel, makes it an ideal material for load-bearing implants, such as joint replacements, a property employed in many more cases and always beneficial.

• **Non-toxic and inert:** titanium is, by nature, a non-toxic material for the human body, a property that is critical in medical applications.

• **Osseointegration**: a process through which titanium integrates with bones, forming a strong bond and ensuring the stability and longevity of implants.

• **Flexibility and ductility:** although a strong material, titanium can easily be bent into the shapes and geometries required for specific applications, creating tailor-made structures for medical devices and biomedical implants.

Titanium and its alloys are fundamental in the development of biomedical devices and implants. Their combination of strength, lightweight, biocompatibility, and corrosion resistance ensures their success in critical applications such as orthopedic and dental implants, cardiovascular devices, and prosthetics (Marin and Lanzutti, 2023; Baltatu *et al.*, 2019a). With ongoing research and development, titanium alloys continue to be optimized for better performance and enhanced patient outcomes in the biomedical field.

Given its properties, titanium is a great material, and when alloyed with other elements, it can be optimized for industrial and biomedical uses. Titanium alloys typically consist of pure titanium combined with other elements, such as

Al, V, Nb, Mo, and Zr, with the main goal being the improvement of targeted properties, strength, toughness, or biocompatibility (Kong *et al.*, 2021).

In normal conditions, such as room temperature and with no outside influencing factors, pure titanium has a hexagonal close-packed structure, mainly known as α-titanium. A stable structure for as long as the temperature of the material is not over 880ºC, reaching that certain temperature makes changes in the structure of the pure titanium, transforming the hexagonal closed-packed in a body-centered cubic structure. A change that can also occur when certain materials are added to the pure titanium, lowering the temperature needed for the transformation, these materials are called β-stabilisers, and some examples include Mo, Nb, Ta, V, Cr, Fe, and Co.

The β-stabilisers are a main class of materials that include the two categories of elements: β-isomorphous elements and β-eutectoid elements, whose roles differ from one another. While β-isomorphous lower the temperature needed for the transition to β-titanium, the β-eutectoid elements, on the other hand, are a composition that stabilizes the β-phase.

While titanium alloys have three main categories, the α-phase, β-phase, and α+β-phase, certain subcategories exist, these being the quasi-α, which contain small traces of the β-phase; the quasi-β, being a phase almost near the β-phase; and the metastable-β phase, an unstable phase stabilized through the addition of stabilizing elements, such as vanadium, molybdenum, and iron (Nada *et al*., 2024; Ahmad and Hussain, 2020).

Titanium alloy phases are presented in Fig. 2.

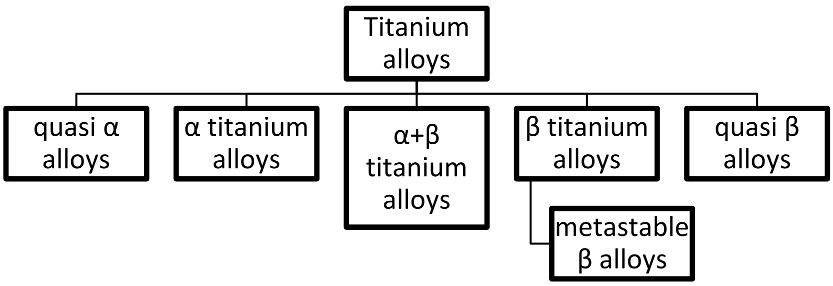

Fig. 2 – The phases of titanium alloys.

2.1. Alpha titanium alloys

Alpha titanium alloys (α-Ti) are titanium alloys whose structure is hexagonal closed-packed (HCP for short). The alpha phase is stable below the transus temperature of ~882ºC; it is strong and ductile with limited formability, provides significant hardness and fatigue resistance at lower temperatures, and also has excellent corrosion resistance. It is a material mainly used in aerospace structures and medical implants and can also be used in chemical industries and marine applications. Table 2 presents examples of these alloys.

Table 2
Examples and uses for alpha and near alpha titanium alloys

Alloy composition	Key properties	Primary applications
Commercially Pure Ti	Weldability and formability, high strength and corrosion resistance	Aerospace and aircraft components, biomedical implants
Ti-5Al-2.5Sn	Good weldability and formability, high strength and corrosion resistance	Aerospace and aircraft components, marine, chemical industries
Ti-8Al-1Mo-1V	High strength, fracture resistance, corrosion resistance and weldability	Aerospace components, marine and chemical industries
IMI-834	Increased tensile strength and creep resistance	Aerospace components

2.2. Beta titanium alloys

Beta titanium alloys (β-Ti) are titanium alloys with a body-centered cubic crystal structure that mostly form at higher temperatures. They are very flexible, easy to shape, and can go through big plastic deformations. It's a stable phase when the temperature is above the α to β transus temperature or can be stabilized using the β-stabilizing elements. The β phase is easier to deform compared to the α phase but at the same time has great toughness, fracture resistance, and high tensile strength at elevated temperatures. Its usage includes aerospace and automotive applications and components. Table 3 provides examples and applications for this type of alloy.

Table 3
Examples and uses for beta titanium alloy

Alloy composition	Key properties	Primary applications
Ti-5Al-5V-5Mo-3Cr	High strength, toughness, and corrosion resistance	High-temperature applications such as aircraft and aerospace components and turbines
Ti-3Al-8V-6Cr-4Mo-4Zr	High-strength, lightweight, and corrosion-resistant	Aircraft springs, tubes, and casing in chemical processing, racing equipment
Ti-4.5Sn-6Zr-11.5Mo	High strength, excellent stress resistance, cold formability, and hardness	Aircraft equipment and sheet metal parts
Ti-8Mo-8V-2Fe-3Al	Enhanced corrosion resistance, ductility, durability, and tensile strength	Aerospace structures, chemical processing equipment

2.3. Alpha+beta titanium alloys

Alpha+beta titanium alloys (α+β-Ti) are a mixture of alpha and beta phases in titanium alloys, providing a balanced combination of strength, toughness, and ductility, perfect for various applications and components in industries. The phase contains both hexagonal closed-packed and body-centered cubic crystal structures. The mixture offers both high strength and excellent formability. The properties can be further enhanced through various surface treatments, such as solution heat treatment or aging. The aerospace, medical, marine, and chemical industries can use this alloy class due to its combination of good properties. Examples of alloys and their uses are presented in Table 4.

Table 4
Examples and uses for alpha+beta titanium alloys

Alloy composition	Key properties	Primary applications
Ti-6Al-4V	High strength, good fatigue resistance, excellent corrosion resistance	Aerospace components, biomedical implants, military applications
Ti-3Al-2.5V	Lower strength when compared to others, excellent corrosion resistance and weldability	Aerospace components, marine, chemical industries
Ti-6Al-2Sn-4Zr-6Mo	Good creep resistance, high strength at high temperatures	Turbines, exhaust, engines, and chemical processing equipment

The transition between the phases is strongly affected by temperature and alloying elements. The transus temperature is approximately 882ºC when these elements are not present, but they can change the temperature to favor one of the phases or a mix of the two.

The purpose of alpha-stabilizing elements is to increase the stability of the alpha phase by lowering the temperature at which the transus to the β-phase occurs. One of the significant stabilizing elements is Al, significantly lowering the transus temperature. Not only this, but aluminum increases creep resistance and corrosion resistance, a fact emphasized by its presence in beta and alpha+beta alloys. Following the importance of aluminum, another beneficial stabilizer is O, and although it increases strength, it can reduce ductility, and in high concentration, can make the material brittle and unusable, meaning that the concentration of oxygen in the material needs a tough control. *C* is another good stabilizing element, alongside *N;* both can increase strength, toughness, and wear resistance (Chen *et al.*, 2024). Similar to the excess of oxygen, a high concentration of carbon or nitrogen can also lead to brittleness.

The alpha stabilizers are used for the enhanced thermal stability of the material, the strength-granting properties at the cost of ductility, but their concentration needs to be closely followed to not damage the material.

The beta-stabilizing elements enhance the stability of the beta-phase, the material maintaining its body-centered cubic crystal structure at lower temperatures, or in some cases at room temperature. The importance of having beta alloys at lower temperatures is given in cases where formability is of vast importance. Furthermore, having a material stable both at low temperatures, such as room temperature, and high temperatures, the usual ones for the beta phase, is of importance in various aircraft, chemical, and automotive industries.

As a result of adding V, the alloyed material has lower corrosion resistance (Çömez, 2023), but it also raises the transus temperature and keeps the beta phase stable at lower temperatures. V also improves resistance to creep and high temperatures. In addition to raising the transus temperature, Mo makes alloys stronger at high temperatures and better at resisting creep and corrosion. However, it makes the alloys less flexible. Similar to Mo, Cr also enhances corrosion resistance, but at high concentrations, it diminishes both ductility and toughness. Another notable stabilizing element is Nb, which significantly impacts the transus temperature of alloys, enabling the beta alloy to exist even at room temperature. In addition, Nb enhances strength, creep resistance, and corrosion resistance, at the cost of reduced elasticity (Cardoso *et al*., 2023).

Alongside alpha and beta-stabilizing elements, we have neutral elements–elements that contribute to the overall performance of the alloy without influencing either phase. Elements such as Sn and Zr are usually used to improve the properties of alloys, for example, improving corrosion resistance, enhancing weldability, and improving toughness and ductility (Norihiko *et al*., 2024; Kong *et al*., 2021).

Applications dictate the choice of alloying elements, which significantly influence the properties and performance of alloys. With a wide range of properties and applications, titanium alloys can be tailor-made for specific parts or given a wide array of options, all this thanks to alloying elements, allowing for the selection of alpha, beta, and alpha+beta titanium alloys, whilst ensuring an optimal combination of strength, ductility, corrosion resistance, malleability, or high-temperature stability. The key to the optimization of titanium alloys for targeted applications stands in the understanding of alloying elements and their impact.

3. Extraction and Production of Titanium

Titanium is an important material in several industries due to its properties; however, the extraction and production of high-quality performing alloys is an advanced operation. Starting from the extraction, followed by the

Kroll or Hunter method, and in the end, the incorporation of alloys for better properties, titanium follows a strict journey with many steps.

Titanite is primarily found in ores such as anatase, brookite, ilmenite, rutile, and titanite. Mining these ores is a important step in determining the overall cost-effectiveness and efficiency of the titanium production process. For the mining process, the employed techniques are dry mining, underground shafts, and open-pit mining. The steps following the mining processes usually include the grinding and crushing of the ores and the purification; titanium is then shaped and treated for applications. The sheet flow of titanium fabrication is presented in Figure 3.

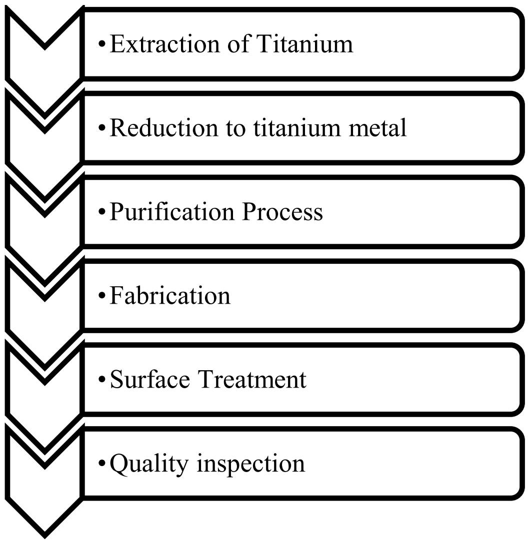

Fig. 3 – Sheet Flow for the Fabrication of Titanium.

The reduction to titanium metal is a step that can occur only after the chlorination of titanium dioxide and obtaining titanium tetrachloride. When the Kroll Method or the Hunter Method is used, titanium tetrachloride is broken down into titanium and magnesium dichloride. When the Hunter Method is used, titanium and sodium chloride are formed (Maldybayev *et al.*, 2024; Okabe and Takeda, 2020).

For the purification of the titanium collected, the methods used are vacuum distillation or arc melting. The finishing touches refer to surface treatments and include anodizing or coatings. The final inspections encompass a range of tests, including dimensional inspection, mechanical property testing, and chemical testing.

As an alternative to the Kroll process, the electrolytic reduction of titanium and the hydride-dihydride process are also ways to get titanium. These methods are still being studied in order to make the process cheaper and better for the environment.

Obtaining titanium from its ores is an important first step that dictates the direction in which production is headed, the cost, the impact on the environment, and how fast the material is obtained, reasons for which the study of new methods is always a great idea.

4. The Characterization of Titanium Alloys

The properties of the titanium alloys are well suited for several applications, but there is always room for improvement where alloys have specific targets and the need to be tailor-made. Understanding the mechanical, thermal, and chemical properties is what allows for their optimization.

The chemical and physical properties of titanium are presented in Table 5.

Table 5
Chemical and physical properties of Titanium

Information		Chemical Properties		Physical Properties	
Name	Titan (Ti)	Atomic Mass	47.867	Natural State	Solid
Chemical Class	Transition Metal	Atomic Radius	140 pm	Melting Point	1941 K
Density	4.506 kg/m^3	Oxide	Amphoteric	Boiling Point	2560 K
Colour	White-Silver	Crystalline Structure	hexagon	Molar Volume	$10.64 \cdot 10^{-6}$ m^3/Kmol

This chapter will discuss the various methods used in the characterization of titanium alloys, going from microstructure analysis to methods used to inspect corrosion resistance, mechanical behavior, and phase transformation. The information is based on Rusu *et al.* (2012).

4.1. Microstructural characterization

The alloying elements, processing techniques, and heat treatments influence the microstructure, which is crucial for understanding the properties and behavior of titanium alloys. The go-to methods for microstructural analysis are optical microscopy, SEM (scanning electron microscopy), and TEM (transmission electron microscopy).

Optical microscopy allows for the observation of grain size, phase distribution, and the detection of defects (Myslyvchenko *et al.*, 2021).

When you combine energy dispersive x-ray spectroscopy with SEM, you can get high-resolution pictures of the surface microstructure. This can help you figure out what chemicals are in different parts of the titanium alloys (Lypchanskyi *et al.*, 2024; Mello *et al.*, 2020).

Transmission electron microscopy, similarly to SEM, provides high-resolution images, but unlike SEM, TEM shows a 2D image projection of the sample.

4.2. Mechanical characterization

The mechanical characterization includes a series of tests for the alloys; these are as follows (Nazarov, 2022):

- Tensile strength: by applying a uniaxial tensile load to a sample, one can determine the yield strength, tensile strength, and elongation.
- Hardness–measures a material's resistance to plastic deformation, and the wear resistance it provides correlates to its strength. The most common methods include the Vickers, Rockwell, and Brinell hardness tests.
- Fatigue–testing that includes repeated loading of the material, either compression-compression, tension-tension, or the combination of the two.

4.3. Corrosion resistance

The oxide layer that forms on the surface of titanium alloys makes them resistant to corrosion. This is a great standard property, but if titanium alloys are left in harsh environments for a long time, they may not last as long as expected, which is why testing is important. The methods utilized to test the corrosion resistance of the material are electrochemical techniques and salt spray testing.

Salt spraying is the exposure to a salt solution in a special chamber by the same name as the test, the duration of which varies; the shortest period is usually one day.

The electrochemical techniques are *potentiodynamic polarization testing, which implies the immersion of a sample in an electrolyte while applying voltage; Immersion testing*, as the name suggests, is the immersion of a sample in a corrosive medium for 30 to 90 days; *cycling corrosion testing* is a cycle of exposure to salt spraying, drying, and humidity.

4.4. Phase analysis

The phase composition of titanium alloys affects their applications, so it's important to analyze which phase is used. The methods for the test are X-ray diffraction and differential scanning calorimetry.

Characterization in titanium alloys is one of the most important steps for its role in industrial applications. Multiple tests are needed to occur for the study of the material, but this knowledge is also critical for further designs of titanium alloys and, more importantly, enhancing properties for targeted applications.

5. Applications of Titanium Alloys

The properties of titanium, whether alone or alloyed, contribute to its great reputation and are evident in many applications. This chapter will highlight the most significant modern applications of titanium alloys, including aerospace, medical, marine, automotive, and industrial applications.

5.1. Aerospace applications of titanium alloys

Titanium alloys are integral in the aerospace industry thanks to their high strength-to-weight ratio, high corrosion resistance, and high-temperature resistance, used for engine parts, airframes, and landing gear.

The alloys are widely used in engine components like turbine blades, compressors, and casings thanks to the lightweight properties they offer, while alloys like Ti-6Al-4V and Ti-5Al-2.5Sn are favored in high-temperature sections of the engine. At the same time, the corrosion resistance plays a crucial role in the longevity and performance of aircraft; as such, titanium alloys are employed for the construction of wings and fuselages. This information is based on studies conducted by Gialanella *et al.* (2020) and Zhao *et al.* (2022).

5.2. Medical applications

Titanium is the preferred material in the medical field for implants, prostheses, and equipment due to its biocompatibility, corrosion resistance, and ability to integrate into the bone structure.

Orthopedic implants, such as hip replacements and knee implants, have certain strength and corrosion resistance requirements, together with the need to promote osseointegration, alloys like Ti-6Al-4V (Baltatu *et al.*, 2019a).

In the same field, titanium alloys play an important role in dental implants and other medical devices. Medical implants and devices benefit from both the corrosion resistance and non-reactive nature of titanium alloys, according to Marin and Lanzutti (2015) and Khorasani *et al.* (2015).

5.3. Automotive industry

Likewise for the aircraft industry, the need in the automotive one is that of a material that can withstand the high temperatures of the engine while also creating a durable but lightweight automobile with a protective casing. Exhaust systems, engine turbines, suspensions, valves, and certain body kits utilize titanium alloys. Due to the difficulties of shaping titanium, race cars primarily benefit from its properties (Furuta, 2019).

5.4. Marine industry

The marine industry found more uses for titanium alloys due to their exceptional resistance to seawater corrosion. The primary applications for these alloys include marine structures such as ship hulls, propellers, and underwater pipelines, as well as desalination plants, heat exchangers, pumps, and piping systems (Oryshchenko *et al.*, 2015).

Like most metals, titanium allows for recycling and sustainability; its longevity and many uses actually show the demand for these actions. Current studies indicate that recycling titanium is not as easy and forward as it may seem. Given the iron and oxygen impurities found in the scraps, titanium is quite difficult to recycle, or better said, has a high price. For these reasons, the production cost of titanium needs to be lowered, titanium needs to be used more commonly, and further studies need to be developed (Takeda *et al.*, 2020).

Titanium is already a very important element in the industry; further study will only elevate this material, challenging further than the automotive, medical, and aerospace industries.

6. Conclusions and Future Directions

Titanium alloys are used in many applications, including biomedical ones, thanks to their properties; however, like other materials, titanium alloys come with both advantages and disadvantages in certain applications. We went over the various advantages titanium alloys have; as for the disadvantages, these include high production cost, limited wear resistance, difficulty in making, lower modulus of elasticity, the need for surface modification, limited strength in some cases, and critical attention to its purity and alloying elements. While these are not disadvantages, the design of biomaterials presents additional challenges, including material biocompatibility, degradation, and long-term safety.

When considering a biomaterial, the requirements it has include biocompatibility, sterilizability, mechanical compatibility, high corrosion resistance, high wear resistance, and osseointegration.

Biocompatibility is one, if not the most important, property of biomaterials, including titanium alloys, and is usually defined as the ability to interact with the human tissues without causing adverse reactions (Baltatu *et al.*, 2019b). It is clear that the biocompatibility also refers to the chemical reactivity of the material, reactions that need not influence the tissues it comes in contact with, but allowing these reactions to benefit the material, one such example is the oxidation of titanium alloys, whereby it creates an outside oxide layer, making the material more durable at no cost for the living system that is found in contact with. Another example of a beneficial process of biomaterials is osseointegration. The migration of bone cells to the surface of the biomaterial forms a bond between the selected material and the bone. The macro/micro-design of the implant and its chemical and physical characteristics influence osseointegration (Hudecki *et al*., 2019).

When it comes to properties like being able to be sterilized, being mechanically compatible, having high corrosion resistance, and high wear resistance, the alloying elements and processing methods used have a big impact.

The future for the use of titanium alloys in biomedical applications looks promising. Some of the key aspects of innovation are customized implants; with the advancements in 3D engineering, the materials can be made to more easily suit the patients, allowing for the design and production of custom-made implants, resulting in improved outcomes for bone-engineered implants (Ringer and Qian, 2023).

Another aspect is related to the biocompatibility and osseointegration. Thanks to ongoing research on surface treatments and its focus on enhancing the surface properties of titanium alloys, we could see treated materials with faster and more effective osseointegration. Surface treatments, bulk modifications, biologic incorporations, coatings, and alloy modifications aim to make titanium more suited for human tissue interactions and accelerated healing time (Bandyopadhyay *et al.*, 2023).

Yang and Hong (2024) did a study that suggests using nanostructured calcium-incorporated surface treatment to improve bioactivity and bone cell and apatite formation. This makes the material more biocompatible and helps it fuse with bone. Other methods of improving these properties are through chemical methods: surface coatings, electrochemical anodizing, chemical depositions, and etching (Sarraf *et al*., 2022). Efforts are being made to enhance mechanical properties such as fatigue resistance, elasticity, and wear resistance, with the goal of achieving long-term use in high-stress applications.

Although the easiest solution is the usage of alloying elements such as Al and V, the benefit to its properties comes at the cost of implant biocompatibility; as a result, cpTi needs a rework and further study for the improvement of its properties through surface modifications (Pesode and Barve, 2023).

Functionalizing surfaces with bioactive molecules and antimicrobial agents could better sterilize alloy surfaces, thus improving implant success rates. Further refinements can be considered, examples being surface texturing to improve cellular adhesion (Yang and Hong, 2024).

Biodegradable titanium alloys can gradually dissolve and be absorbed in the human body, eliminating the need for removal surgeries and benefiting applications like temporary implants. Magnesium is degradable and gets absorbed in the body; as for the titanium, thanks to its biocompatibility and osseointegration, there exists the possibility of full integration in the bone. While a metallic biomaterial, biodegradable titanium alloys actually refer to magnesium-based alloys with titanium being one of the alloying elements. Due to its biocompatibility and biodegradation, magnesium is a beneficial material for medical applications; however, its rapid degradation rate and low corrosion resistance present challenges. Researchers are studying and proposing Mg-Ti alloys to mitigate issues, such as enhancing corrosion resistance while maintaining biocompatibility (Sharma *et al*., 2024). Titanium plays a significant role in many industries; the focus right now is to further improve its workability, from new alloy designs to improving its properties through surface modifications, and more importantly, to study ways to reduce the risk taken when choosing titanium for biomedical applications.

Recent studies have demonstrated methods for enhancing fatigue resistance, enhancing biocompatibility, and enhancing longevity, but these are not the only advancements. Other important factors to look forward to are reducing production costs and improving recycling. In conclusion, reducing production costs and improving recycling are important factors to look forward to.

The properties titanium alloys offer are essential for industrial applications; the problems that arise are cost-related and accessibility-related. Through the studies for an easier development cycle, titanium could make its way into more applications, in turn raising the interest towards the material and empowering its study, a cyclical process that starts with making titanium and titanium alloys more accessible, promoting its study, and repeating. Through continuous research and innovation, the use of titanium and its alloys can only go up.

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ALIAJE AVANSATE DE TITAN PENTRU UTILIZĂRI MEDICALE ȘI INDUSTRIALE

(Rezumat)

Scopul acestui articol este de a discuta metode de îmbunătățire a proprietăților aliajelor de titan, investigând diferite strategii de intensificare a durității materialului, rezistenței la coroziune, și cel mai important biocompatibilității, cu accent pe performanță mecanică, integritate structurală și biocompatibilitate, potrivite implanturilor ortopedice și dentare. Lucrarea examinează efectele diferitelor elemente de aliere și impactul pe care îl au fazele titanului asupra proprietăților sale. În plus, articolul discută și despre metodele de producție, plecând de la extragere până la tratamente de suprafață, și include metode de caracterizare structurală, testare mecanică, evaluarea rezistenței la coroziune. Titanul și aliajele sale sunt apreciate pentru raportul duritate-greutate, buna rezistență la coroziune, flexibilitate și biocompatibilitate, făcându-le potrivite pentru o gamă variată de aplicații, ce vor fi detaliate în această lucrare. Propunerile viitoare pun accent pe proiectarea cu imprimante 3D, pentru dezvoltarea implanturilor personalizate, modificări de suprafață pentru îmbunătățirea biocompatibilității, și explorarea opțiunilor de aliaje biodegradabile.

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ADVANCED OPTOELECTRONIC TECHNOLOGIES FOR IN-SITU ANALYSIS OF METALLIC WELD BEADS: COMPARISON WITH CLASSICAL EDS METHODS

BY

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Abstract: This paper presents the results of a study on the development of portable, modular optoelectronic equipment for the in situ qualitative and quantitative analysis of metallic weld beads. Compared to traditional analysis methods, such as EDS spectrometry, the proposed systems offer superior accuracy, real-time analysis capabilities, portability, and energy autonomy. Three patented devices are presented: a portable device without an excitation source, a portable device with a laser excitation source, and a complex modular spectromicroscope. A comparative evaluation was conducted to highlight the advantages of these devices in terms of sensitivity, application flexibility, and integration into production processes.

Keywords: metal welding; light element detection; spectral characterization.

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1. Introduction

The chemical composition of weld beads must be analyzed to ensure the quality of metallic joints. Conventional methods, including EDS, require the extraction of samples, followed by sample preparation and post-process analysis. These methods are inherently limited in their applicability within dynamic industrial environments. In this particular context, the objective of the research was to develop optoelectronic systems with the capacity to perform analysis directly in the field during the welding process.

2. Materials and methods

Three distinct pieces of equipment have been developed and tested:

- The portable equipment without excitation source (Gutt *et al.*, 2015a) using the radiation emitted by the thermal process as the excitation source for atomic emission spectrometry.
- The portable laser excitation source device (Gutt *et al.*, 2015b) using a medium-power laser to excite the sample, allowing precise control of the analysis parameters.
- The complex modular spectromicroscope (Amariei *et al.*, 2015) enabling multiple spectral analysis (emission, absorption, fluorescence, photoacoustic, fluorescence, Raman) combined with microscopic imaging and automation.

2.1. Portable optoelectronic equipment without excitation source

The equipment comprises a miniature spectrometer, a camera for optical centering, a laser rangefinder for focusing, and a USB interface. The analysis is performed using radiation generated by the welding process and Mikropack SpecLine software. This method facilitates the analysis of chromium (Cr), manganese (Mn), iron (Fe), nickel (Ni), and silicon (Si) elements without the necessity of sample processing (Goldstein *et al.*, 2018).

2.2. Portable optoelectronic device with excitation source

The portable optoelectronic equipment with laser excitation source enables qualitative and quantitative in situ chemical analysis by atomic emission spectrometry. The system's efficacy is attributed to the medium-power laser source and integrated telemeter, which ensure precise sample excitation and a constant focus distance, thereby contributing to the accuracy of the results. The equipment is powered by a car battery, is entirely autonomous and portable, and is well-suited for industrial field applications. The compact structure incorporates a miniature spectrometer, a fiber optic system, and a digital interface, thereby enabling rapid, non-destructive, and reproducible analysis of metallic materials.

2.3. Modular complex spectromicroscope

The system incorporates an Nd:YAG source, UV-VIS-NIR spectrometers, a video microscope, and modules for photoacoustic, fluorescent, and Raman analyses (Gutt *et al.,* 2011). This apparatus is capable of performing simultaneous analyses of chemical composition and thermal distribution during the welding process. Its applications include fundamental research and industrial inspection (Bernevig-Sava *et al*., 2019).

3. Experimental methods

The experimental tests were conducted under controlled conditions in the Materials Testing and Characterization Laboratory (Bernevig-Sava *et al*., 2019). The metal samples that were analyzed included carbon steel, stainless steel, copper, and aluminum. For each material, weld beads were fabricated using an electric arc and a Nd:YAG laser welding technique, excluding the use of filler material to avoid introducing additional variables. The equipment was utilized in the following manner:

- The equipment without an excitation source was positioned in the proximity of the electric arc, focused using a laser telemeter on the area of maximum plasma emission, and the spectra were automatically acquired at the points of maximum emission, as identified by the dedicated software.
- The laser source equipment was configured to emit pulses of 8 kW, 60 J, at 1064 nm, focused on the surface of the weld bead. The optimal excitation distance was maintained constant through the use of an optical feedback telemeter.
- The modular spectro-microscope was configured for sequential measurements: UV-VIS for atomic emission, NIR for molecular absorption, and fluorescence for impurity identification. The automatic calibration was executed using the integrated optical software, and the results were then correlated with the microscopic images.

For comparative purposes, the same samples were also analysed using EDS (Energy Dispersive X-ray Spectroscopy) on a Hitachi SU-70 SEM microscope equipped with an Oxford Instruments EDS energy dispersive spectrometer (Goldstein *et al*., 2018).

4. Results and discussions

The utilization of portable devices in the acquisition of spectra has been demonstrated to yield more intense and stable signals, a consequence of the employment of multiple spectral averages and the automatic signal averaging system.

The laser systems employed in actively excited equipment facilitate precise detection, even of elements with low atomic mass, thus surpassing the well-known limitations of EDS in this field.

Table 1 provides a clear overview of the key differences between the classic EDS system and the patented equipment. The patented equipment has multiple advantages: firstly, it does not require sample extraction, secondly, it allows real-time analysis, thirdly, it has excellent portability and high sensitivity to light elements (through spectral averaging). Furthermore, the device can be integrated with the welding process through temperature control. Conversely, the conventional EDS system necessitates sample extraction, restricts real-time analysis, and exhibits limitations in detecting elements with $Z < 11$. It has been demonstrated that the patented equipment necessitates lower operating and maintenance costs.

Table 1

Comparative features of classic EDS technologies and the patented equipment

Comparative feature	**EDS Clasic**	**Patented equipment**
Need for sample extraction	Yes	No
Real-time analysis	No	Yes
Portability	Reduced	Very good
Type of analysis	Qualitative + quantitative	Qualitative + quantitative
Light elements sensitivity	Limited ($Z < 11$)	High - through spectral mediation
Integration with the welding process	No	Yes (through temperature control)
Cost of operation and maintenance	High	Low

The following table provides a comparison (Table 2) between the proposed methods and the classical EDS method:

Table 2
Comparative results of classic EDS technologies and the patented equipment

Parameter	**Portable optoelectronic equipment**	**Modular Complex Spectromicroscope**	**EDS Oxford Instruments**	**Comments**
Detected elements	Fe, Cr, Mn, Ni, Si	Fe, Cr, Mn, Ni, Al, Cu	Fe, Cr, Mn, Ni, Si	Comparable detected elements
Accuracy (%)	±2%	±1%	±1%	Accuracy comparable to EDS
Analysis time	4 s	3-5 s	60-90 s	Much shorter time to developed methods
Portability	Very high	Medium	Low	EDS requires laboratory
Need for sample processing	No	Minimum	Yes	EDS requires sampling and polishing

Figure 1 illustrates the disparities between the examined methodologies. The following analysis provides an average time for each method.

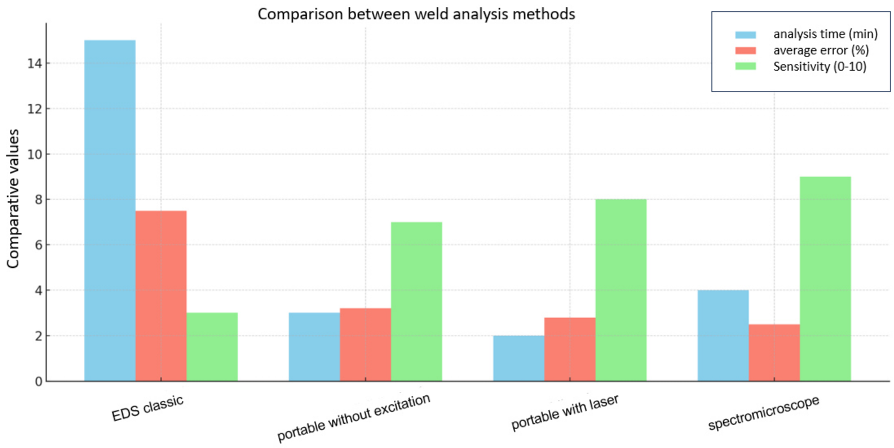

Fig. 1 – Graphical representation of the differences between the analyzed methods.

The estimated relative error percentage is contingent upon the analysis method employed. The relative sensitivity of the methods is demonstrated by the arbitrary score.

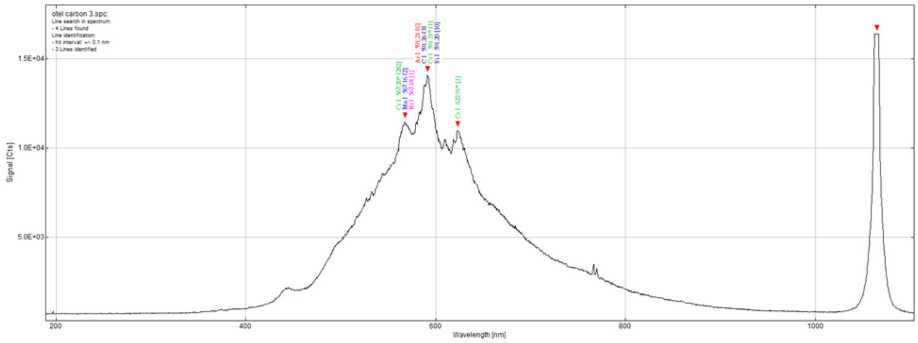

Fig. 2 – Spectrum emitted by thermal plasma in laser welding of carbon steel.

As illustrated in Fig. 2, the process of identifying spectral lines and elements in thermal plasma during laser welding of a carbon steel sample utilises a complex modular spectroscope and Mikropack SpecLine software.

Comparative tests were performed between the complex modular spectromicroscope and the Shimadzu EDX-900HS X-ray dispersive spectrometer, using welded samples of carbon steel and stainless steel (Woldman, 2020). The evaluations were performed on the same weld beads, analyzing the elements Cr, Ni, Mn, and Si. The observations that were made were as follows:

- The accuracy of Cr and Ni determination was higher for the modular spectromicroscope (error <2%) compared to the Shimadzu EDX-900HS. (4–5%).
- The detection limit for light elements (Si, Mn) was lower in the case of the modular system.
- The flexibility of the analysis included combined spectroscopy (UV-VIS, Raman, fluorescence) and topographic visualization.
- Total analysis time: ~4 min (spectromicroscope) vs. >15 min (EDX-900HS).

These results support the superiority of the modularity and analysis speed of the developed system, especially in in situ applications.

5. Conclusions and perspectives

The developed systems represent a viable and technologically superior alternative to classical EDS methods, especially in applications where fast, accurate, and non-destructive analysis is essential. The integration of real-time analysis with welding parameter control offers opportunities for the development of automated and intelligent industrial processes.

Further research is recommended on the applicability of these technologies in areas such as aerospace, energy, and additive manufacturing (metal 3D printing), where real-time composition control is critical.

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TEHNOLOGII OPTOELECTRONICE AVANSATE PENTRU ANALIZA IN SITU A CORDOANELOR DE SUDURĂ METALICE: COMPARAȚIE CU METODELE CLASICE DE TIP EDS

(Rezumat)

Acest articol prezintă rezultatele cercetărilor privind dezvoltarea unor echipamente optoelectronice portabile și modulare, destinate analizei calitative și cantitative in situ a cordoanelor de sudură metalice. Comparativ cu metodele clasice de analiză, cum ar fi spectrometria EDS, sistemele propuse oferă o precizie superioară, capacitate de analiză în timp real, portabilitate și autonomie energetică. Sunt prezentate trei echipamente brevetate: dispozitivul portabil fără sursă de excitație, echipamentul portabil cu sursă de excitație laser și spectromicroscopul modular complex. Evaluarea comparativă evidențiază avantajele acestora în ceea ce privește sensibilitatea, flexibilitatea aplicativă și capacitatea de integrare în procesele de producție.

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WORK ENVIRONMENT: A FACTOR THAT INFLUENCES EMPLOYEE PERFORMANCE

BY

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Abstract. The work environment consists of all the factors that surround employees and the space in which they perform their tasks. Today's workers seek more than just a well-paying job; they desire a meaningful workplace with a positive culture that promotes a balance between their professional and personal lives. They also value opportunities for personal and professional growth, along with a sense of appreciation and respect. A healthy work environment is essential in any organization, as it brings advantages that directly and indirectly benefit both the company and its employees. This paper aims to provide a thorough examination of the various work environments present in different organizations. By utilizing an exploratory research approach, the study seeks to identify the work environments that employees prefer and those that companies adopt, which have resulted in enhanced human resource performance and positively impacted organizational.

Keywords: Work environment, working conditions, productive work, job satisfaction, professional life.

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1. Introduction

When organizing the work of employees, employers must consider both legitimate interests of the organizations and those of employees. They should ensure that wages are paid for the provision of quality services, and that these wages are comparable to those offered under normal working conditions. Additionally, any intrusion into employees' personal lives should be minimized. Employers must create jobs to meet their organizational objectives, while also fostering work environments that support the physical, psychological, and social well-being of employees in the workplace.

The term "work environment" refers to the set of conditions (physical, psychosocial, technological and organizational) in which employees carry out their work, directly influencing their performance, job satisfaction and well-being. Work environments are more than just a place where people work; they shape the company culture, promote employee well-being and lead to better organizational outcomes, creating a positive work environment. A well-designed/optimized work environment is essential for maximizing efficiency, fostering collaboration, and enhancing employee motivation. The work environment can be examined from both physical and non-physical perspectives. Physically, this includes aspects such as the appearance of the workspace, furniture, lighting, temperature, air quality, noise levels, the technologies employed, and areas designated for relaxation. On the other hand, non-physical aspects encompass company values, organizational culture, leadership styles, interpersonal dynamics, as well as themes of diversity and inclusion.

All these aspects encourage respect, collaboration, creativity, teamwork and open communication between employees within organization. Hence, employees with increased motivation and job satisfaction add value to the entire organization.

2. Factors that influence the work environment

The work environment encompasses everything that surrounds employees, that influences how they perform their work tasks. It includes both external and internal factors that can impact employee morale, and, consequently, he or she overall the productivity. A productive workplace requires an environment that supports achieving desired outcomes. Conversely, an inadequate and unfavorable work environment can result in work-related stress and may lead to employees' skills being underutilized. Hence the strong interaction between employee productivity and the physical environment at work (Pimpong, 2023). In the evolving work landscape, employees' preferences for their work environment are changing. Today's workers are not just looking for a job where they are highly paid, they are looking for a meaningful workplace with a positive work culture that offers a work-life balance, opportunities for personal and professional growth, and a sense of appreciation and respect. A good climate is essential in any organization, and this can only have advantages that have direct and/or indirect repercussions on both the company and the employees.

The work environment encompasses all aspects that influence employees' experiences, from interpersonal interactions to overall job satisfaction. In essence, it refers to the setting in which tasks are carried out. Its quality can vary significantly depending on the organization, directly impacting both employee well-being and organizational performance.

A supportive organizational climate plays a vital role in shaping positive work outcomes; when the environment is supportive, employees are more likely to perform at their best atmosphere is supportive, employees are more likely to perform at higher levels. Therefore, fostering a healthy work environment is essential for achieving organizational goals. An exploration of what makes for a positive or negative, environment in the workplace begins with defining the key components of the environment itself, which is made up of various factors (Fig. 1).

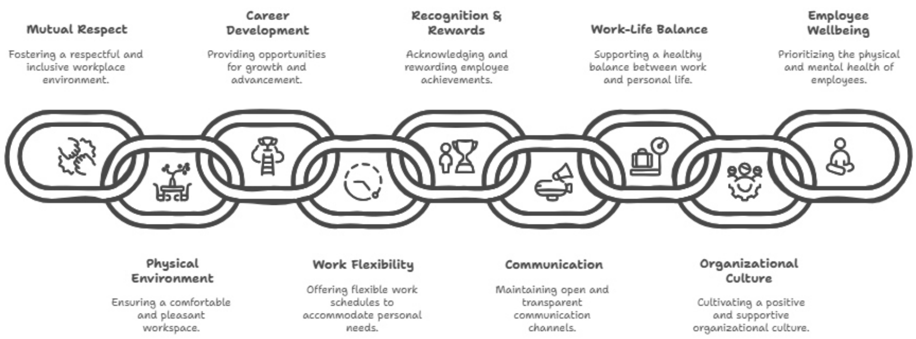

Fig. 1 – Key factors for employee satisfaction, own adaptation after (Beaumont-Oates, 2023; Pimpong, 2023; Phuong and Vinh, 2021; Rusu *et al.*, 2016; Turnea *et al.*, 2020).

As presented in Fig. 1, among the factors identified as the most common are:

Mutual respect serves as the cornerstone of a healthy organizational culture. Each employee deserves to be treated with dignity, and leaders should lead by example. When mutual respect is present, it enhances collaboration and builds trust among team members.

Comfortable and pleasant physical environment can improve employee mood and productivity. Well-designed physical workspace can elevate mood, reduce stress, and enhance productivity. Factors such as natural lighting, ergonomic furniture, relaxation areas, proper ventilation, and regulated temperature all contribute to a favorable work atmosphere. An aesthetically pleasing and flexible environment supports employees' concentration and fosters a stronger connection to their work, ultimately benefiting both mental and physical well-being. Some factors contribute to creating an atmosphere conducive to concentration and creativity, such as natural light, ergonomic furniture, relaxation spaces, proper ventilation of the space where you work, temperature, cleanliness, noise level.

Career development opportunities. Access to professional development programs tailored to individual needs helps employees grow and enhances their long-term commitment to the organization.

Work schedule flexibility enable employees to balance professional responsibilities with personal commitments. Options such as remote work or adjustable hours often lead to increased satisfaction and productivity.

Recognizing and rewarding performance motivates them to push themselves and contribute more to the success of the organization. Acknowledging individual and team performance motivates employees to contribute actively. A fair and transparent reward system, including competitive compensation packages, bonuses, and benefits, reinforces employee engagement. Conversely, unclear or inadequate compensation structures can diminish motivation and increase turnover.

Transparent communication/ open communication channels allow employees to voice ideas and concerns, while leaders provide constructive feedback and share relevant business information. Transparency fosters a culture of trust and involvement, whereas poor communication practices can undermine morale and lead to disengagement.

By supporting a *work-life balance*, organizations should implement policies and programs that promote balance between work and personal life. Flexible scheduling, leave policies, and wellness initiatives can contribute significantly to overall employee satisfaction

Positive organizational culture - a strong culture based on shared values, collaboration, and innovation enhances loyalty and performance. Clearly defined goals and practices, when consistently applied, guide employee behavior and decision-making. A culture that values diversity, encourages continuous learning, and rewards effort fosters a productive and inclusive environment. Conversely, a disconnect between stated values and actual practices can create a toxic atmosphere

Support for *employee wellbeing* means providing resources for physical, emotional, and mental health is essential. Programs such as wellness initiatives, counseling, and comprehensive health benefits help reduce stress and improve job satisfaction. Additionally, positive social interactions at work contribute to a cooperative and enjoyable environment, reducing tension and strengthening team dynamics.

It is essential to remember that there is no perfect work environment that will please all employees and that suits everyone (Pimpong, 2023). Thus, if one refers to a simple employee, the work environment that suits them today, that ideal environment, for performing a task, may be unsuitable for performing another task on another day or even on the same day. Therefore, many factors influence the work environment, particularly the ability to measure it, as this depends greatly on the expectations, interests, and perceptions employees have of the organization.

3. Types of work environments

When discussing the work environment, one refers to the setting in which work occurs. This includes everything related to the performance of an employee's activity, from how he or she interacts, to what the place where the activity is carried out looks like, to their degree of satisfaction.

In the specialized literature 10 types of work environments have been identified classified into three categories as shown in Fig. 2.

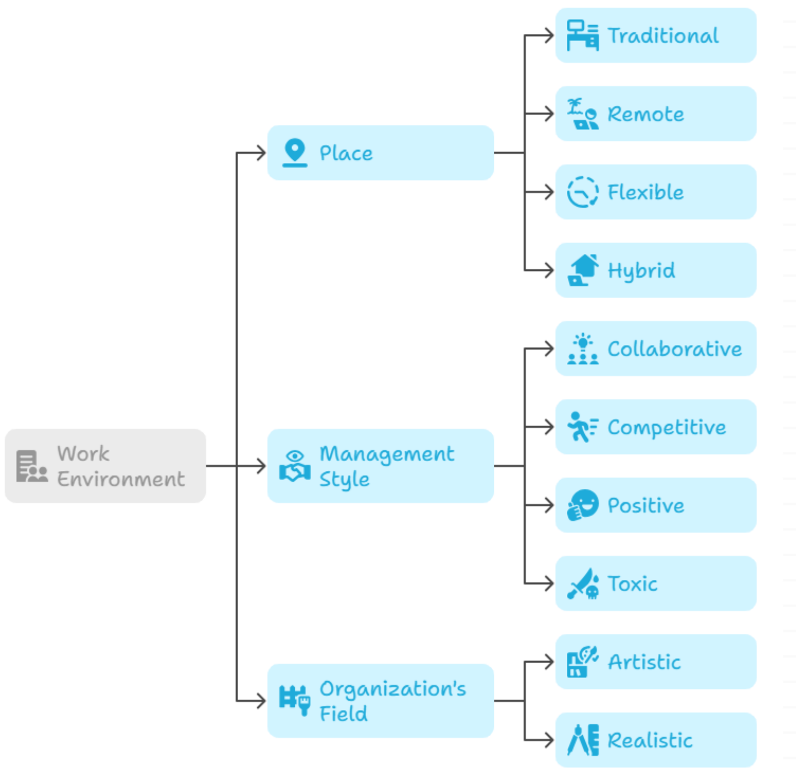

Fig. 2 – Type of work environments, own adaptation after (Badoiu, 2024; Bogathy, 2004; Herrity, 2024; Housman and Minor, 2015; Stoyancev, 2024; https://www.paycom.com/resources/blog/types-of-work-environments).

Traditional or Conventional Work Environment is structured, rule-based, and often hierarchical. It's ideal for people who value routine, stability, and clearly defined roles. While it provides clarity and control, it can also be rigid and limit collaboration and flexibility. This type is often found in banks, law firms, or government institutions.

In *Remote Work Environment* tasks are performed outside of the office, often using digital tools. It's great for individuals who are independent and value flexibility. Remote work offers better work-life balance, but can lead to isolation and communication challenges if not well managed. It's common in tech, creative, and service-based industries.

Flexible work environment goes beyond just location. It includes flexible schedules, roles, and even contracts. Employees are judged more on outcomes than presence. While it fosters motivation and autonomy, it also demands discipline and strong self-management skills.

Hybrid work environment combines both remote and in-office work, offering the best of both worlds. This setup is ideal for people who enjoy flexibility but also benefit from in-person collaboration. However, it requires strong coordination and communication strategies to succeed.

In the case of the *collaborative work environment*, teamwork is the main driver of success. These workplaces value sharing, co-creation, and open communication. Innovation thrives here, but it also requires strong interpersonal skills and clear facilitation to avoid conflict or misalignment.

Competitive work environments are performance-driven and reward individual success. They're ideal for ambitious, high-energy employees. While they boost productivity, they may also create stress, rivalry, and a lack of cooperation if not balanced with team culture.

Comfortable or positive work environment is where well-being, respect, and open communication are central. These environments foster trust, satisfaction, and long-term productivity. They don't have to be informal; they just need to support human potential.

Toxic or harmful work environment is marked by poor communication, micromanagement, or exclusion. It undermines well-being, trust, and performance; while it might produce short-term results, the long-term consequences are serious.

Artistic or creative environments are all about freedom, originality, and expression. These settings encourage innovation and are often informal, with fewer rules. They're great for people in design, media, or the arts, though they may lack structure or performance metrics.

Realistic or practical work environment are grounded in action and tangible results. They're ideal for those who enjoy technical or manual work, and value efficiency and order. While effective, they can become repetitive or inflexible over time.

4. Comparative analysis of work environments

Work environments vary significantly in terms of structure, culture, and expectations, each shaping employee behavior, performance, and well-being in distinct ways. From the stability and predictability of traditional models to the autonomy and adaptability offered by flexible settings, and from the dynamic energy of collaborative or creative spaces to the dysfunctions of toxic cultures, the environment plays a decisive role in organizational success.

Table 1

Comparative analysis of work environments, own adaptation after (Badoiu, 2024; Bogathy, 2004; Dale,2024; Herrity, 2024; Housman and Minor, 2015; Stoyancev, 2024; https://www.paycom.com/resources/blog/types-of-work-environments)

Types of work environments	Advantages	Disadvantages
By the place where the work tasks are carried out		
Traditional or conventional	✓ Stability and role clarity ✓ Strong managerial control ✓ Easy coordination in physical teams	➢ Bureaucracy and rigidity; ➢ Limited collaboration and innovation; ➢ High operational costs (office space, commuting); ➢ Risk of employee demotivation.
Remote	✓ Increased autonomy and flexibility ✓ Better work-life balance ✓ Reduced commuting time and costs ✓ Access to a broader talent pool for employers	➢ Risk of social isolation ➢ Blurred boundaries between personal and professional life ➢ Dependence on technology and internet stability; ➢ Potential difficulties in collaboration and supervision;
Flexible	✓ Higher job satisfaction and motivation ✓ Enhanced productivity through autonomy ✓ Attraction and retention of diverse talent ✓ Promotes innovation and adaptability	➢ Challenges in tracking performance objectively ➢ Need for high self-management and discipline ➢ Risk of communication gaps ➢ Potential inequality if not supported by inclusive policies
Hybrid	✓ Balanced work-life dynamics ✓ Opportunities for collaboration and informal interactions ✓ Enhanced employee satisfaction and engagement ✓ Adaptability to different job roles and preferences	➢ Coordination challenges across locations ➢ Potential inconsistency in team dynamics ➢ Need for strong communication strategies ➢ Risk of unequal access to opportunities or visibility

Table 1

Continuation

Types of work environments	Advantages	Disadvantages
By management style		
Collaborative	✓ Increased innovation through diverse perspectives ✓ Stronger team cohesion and morale ✓ Faster problem-solving and idea generation ✓ Encourages a culture of trust and inclusion	➢ Risk of groupthink or conflict avoidance ➢ Dependency on others may delay progress ➢ Individual efforts may be less visible ➢ Requires strong facilitation and conflict management skills
Competitive	✓ Drives productivity and high performance ✓ Encourages innovation and continuous improvement ✓ Identifies and rewards top talent ✓ Fosters a results-oriented culture	➢ Can lead to stress and burnout ➢ Risk of toxic competition or unethical behavior ➢ May reduce collaboration and team spirit ➢ Difficult for individuals who value balance over pressure
Harmful or toxic	✓ Short-term performance might be high under pressure, but unsustainable ✓ Can trigger temporary compliance, but rarely innovation or engagement	➢ High levels of stress, burnout, and absenteeism ➢ Poor collaboration and trust erosion ➢ Low morale and productivity ➢ High turnover and reputational damage
Comfortable or positive	✓ Higher engagement and retention ✓ Enhanced collaboration and creativity ✓ Reduced stress and improved mental health ✓ Strong organizational culture and reputation	➢ Risk of complacency if not balanced with performance focus ➢ Can be difficult to maintain in high-pressure environments ➢ Potential underperformance if expectations are not clear

Table 1
Continuation

Types of work environments	Advantages	Disadvantages
	By the organization's field of activity	
Artistic or creative	✓ Stimulates innovation and fresh perspectives ✓ High personal investment and fulfillment ✓ Encourages diversity of thought ✓ Often leads to unique products and services	➢ Lack of structure may lead to disorganization ➢ Difficult to standardize or measure performance ➢ Creative blocks or pressure to be original ➢ May not suit all personality types
Practical or realistic	✓ High clarity of roles and expectations ✓ Tangible and measurable outcomes ✓ Stable routines and clear performance indicators ✓ Effective for results-driven operations	➢ May limit creativity and flexibility ➢ Routine work can become monotonous ➢ Limited interpersonal or emotional engagement ➢ Innovation may be constrained by standardization

All the above categories are not always mutually exclusive. For instance, a flexible environment may also foster collaboration, just as an artistic or creative setting may function effectively in a remote format. Conversely, toxic cultures, regardless of sector or performance level, often lead to disengagement, burnout, and long-term organizational damage. Positive work environments, whether structured, flexible, or creative, are typically characterized by a combination of clarity, mutual trust, and psychological safety. Hybrid or mixed models are increasingly common; for example, a creative startup may blend remote work with a highly collaborative culture.

The compatibility between the work environment and the prevailing management style is crucial; a remote setting, for example, requires clear communication and transparent leadership. Moreover, the perception of a work environment is deeply subjective, influenced by factors such as age, professional experience, lifestyle, and local or national culture. There is an interdependent relationship between three core dimensions: spatial setting, management style, and professional domain, their alignment being essential for fostering sustainable performance and employee well-being.

5. Preferred Work Environments. Employees vs. Employers

In general, employees tend to prefer work environments that offer a balance between autonomy, psychological safety, and opportunities for development. Flexible and hybrid environments are often valued for their ability to accommodate individual needs related to schedule, lifestyle, and work-life balance. Collaborative and positive environments, characterized by open communication, mutual support, and a healthy organizational culture, also contribute to job satisfaction and employee engagement. Among employees in creative industries or younger generations, there is an increased preference for artistic, innovative, or self-expressive environments. However, the perception of an "ideal" work environment is influenced by factors such as age, professional experience, individual values, and cultural context, making preferences diverse and dynamic (Zhejing *et al*., 2022).

From an employers' perspective, preferred work environments are those that maximize productivity, facilitate team coordination, and support the organization's strategic goals. Traditional environments remain attractive in industries where control, direct supervision, or confidentiality are essential. However, more and more employers are adopting hybrid or flexible models, recognizing their benefits on staff retention and performance. Competitive environments are preferred in organizations focused on quick results, where pressure can stimulate individual excellence. In contrast, companies in innovative or human-capital-centric sectors opt for collaborative or creative environments that encourage new ideas and teamwork (Jianchun, 2024). Employers' choice of a work environment is often strategic and reflects both the specifics of the field of activity and the organizational culture promoted.

Organizations that have implemented flexible, collaborative, and employee-centered environments have seen significant improvements in human resource performance, innovation, and overall organizational effectiveness. Organizations that have achieved significant improvements in human resource performance have adopted modern work environments centered on employee needs and a balanced approach to both efficiency and well-being.

Creating work environments where employees feel safe, valued, and supported, organizations are able to boost engagement, motivation, and overall performance. At the same time, these environments positively impact long-term organizational outcomes, strengthening competitiveness and corporate reputation.

6. Conclusion

Work environments adopted by organizations have significantly evolved to adapt to both employee needs and the competitive demands of the market. The reviewed studies highlight that the work environment directly influences employee performance, job satisfaction, psychological health, and engagement levels.

Traditional, remote, and hybrid environments provide spatial and temporal flexibility, increasing autonomy and reducing stress, but also posing challenges related to communication and cohesion.

Flexible and collaborative environments stimulate innovation and creativity by facilitating social interactions and idea exchange, while competitive environments may boost individual performance but risk negatively affecting the organizational climate if poorly managed.

Furthermore, artistic and creative environments support personal expression and innovative problem-solving, essential for creative industries, whereas realistic/practical environments optimize processes and operational efficiency.

Toxic or harmful environments demonstrate the negative impact that a deficient organizational climate has on employee well-being and productivity, underscoring the need for interventions to improve working conditions. In contrast, comfortable and positive environments promote a healthy balance between professional demands and personal needs, generating a favorable impact on performance and employee retention.

Overall, the literature supports that organizational success depends not only on strategies and technologies but also on the ability to build and maintain work environments that support mental health, motivation, and employee development. Implementing appropriate work environments tailored to the organization's specifics and employees' needs is essential for maximizing human potential and achieving long-term organizational goals.

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MEDIUL DE MUNCĂ: UN FACTOR CARE INFLUENȚEAZĂ PERFORMANȚA ANGAJAȚILOR

(Rezumat)

Mediul de lucru cuprinde toți factorii care îi înconjoară pe angajați și spațiul în care își îndeplinesc sarcinile. Lucrătorii de astăzi își doresc mai mult decât un loc de muncă bine plătit; ei își doresc un loc de muncă semnificativ, cu o cultură pozitivă care promovează un echilibru între viața lor profesională și cea personală. De asemenea, ei apreciază oportunitățile de creștere personală și profesională, împreună cu un sentiment de apreciere și respect. Un mediu de lucru sănătos este esențial în orice organizație, deoarece aduce avantaje care beneficiază direct și indirect atât compania, cât și angajații acesteia. Această lucrare își propune să ofere o examinare amănunțită a diferitelor medii de lucru prezente în diferite organizații. Prin utilizarea unei abordări de cercetare exploratorie, studiul urmărește să identifice mediile de lucru pe care le preferă angajații și pe cele pe care le adoptă companiile, care au dus la îmbunătățirea performanței resurselor umane și au avut un impact pozitiv asupra organizației.